Project EASME/COSME/2014/014

An analysis of drivers, barriers and readiness factors of EU companies for adopting advanced manufacturing products and technologies

Deliverable 2 (based on Work Package 2):

Drivers and Barriers of EU Companies for adopting Advanced Manufacturing Technologies

submitted by VTT, Helsinki, Finland and
IDEA Consult, Brussels, Belgium

submitted to

European Commission

Executive Agency for Small and Medium-sized Enterprises (EASME)

Unit A.1.5 - COSME, Competitiveness

COV2 11/129, B-1049 Brussels/Belgium

submitted on

29th February 2016

main contact person for this deliverable

Magnus Simons

Business Ecosystem Development

VTT Technical Research Centre of Finland

Vuorimiehentie 3

P.O. Box 1000

FI-02044 VTT, Finland

Phone	+358 40 543 8586

overall project manager

Henning Kroll

Competence Center Policy – Industry – Innovation

Fraunhofer Institute for Systems and Innovation Research ISI

Breslauer Strasse 48

D - 76139 Karlsruhe

Phone	+49 721 6809-181

Fax	+49 721 6809-176

1 (1)

Statement

In the literature study presented in Deliverable 2 of the ManStu project, articles and material related to the topic were identified using the Web of Science data base by Thomson Reuters. To gain full rights to quote the articles VTT has acquired all the articles and textual material cited in the Deliverable 2. A data base of electronic copies of these articles is kept at VTT.

In the Deliverable 2, quotation to third part articles and material has been made according to due process and good practice for quotation in academic work. Direct quotations have been marked with quotation marks. To ensure that quotation of articles has been done properly, the full text of the Delivarble 2 has been checked using an anti-plagiarism tool.

Espoo,

19.05.2016

Peter Ylén

Head of Research Area

Magnus Simons

Principal Scientist (project manager)

Table of Contents

Abbreviations

3D – Three Dimensional

6R – Redesigning, Reusing, Remanufacturing, Recovering, Recycling and Reducing

ABDS – Agent Based Decision Support system

ALD – Atomic Layer Deposition

AM – Additive Manufacturing

AMT – Advanced Manufacturing Technologies

ASV – Annual Sales Volumes

BG – Bioactive Glasses

BGA – Ball Grid Array

BPP – Bipolar Plate

CAD – Computer Aided Design

CAM – Computer-Aided Manufacturing

CCS – Carbon Capture and Storage system

CEO – Chef Executive Officer

CSF – Critical Success Factors

CMOS – Complementary Metal Oxide semiconductor

CNC – Computer Numerical Control

CO_2 – Carbon Dioxide

CPS – Cyber-Physical Systems

CU Boulder – University of Colorado Boulder

DAI – Distributed Artificial Intelligence

DARPA – Defence Advanced Research Projects Agency

DBC – Direct Bonded Copper

DMLS – Direct Metal Laser Sintering

e-MAS – evaluation method for MAS(2)

EF – Emission Factor

EMS – Environmental Management System

EOL – End-Of-Life

ERP – Enterprise Resource Planning

ESB – Enterprise Service Bus

EU – European Union

FDM – Fused Deposition Modelling

FRP – Fibre- Reinforced Polymer

HFD – Hybrid Feed Drive

HRI – Human-Robot-Interaction

i-MAS – information management method for MAS(2)

ICT – Information and Communication Technology

IoT – Internet of Things

IPLC – Industrial Powerline Communication

IT – Information Technology

KET – Key Enabling Technology

KPI – Key Performance Indicator

kWh – Kilowatt hour

LCA – Life Cycle Assessment

LCM – Lithography-based Ceramic Manufacturing

LED – Light-Emitting Diode

LGA – Land Grid Array

LMD – Linear motor drives

LOM – Laminated Object Manufacturing

LTCC – Low Temperature Co-fired Ceramic

LUT – Laser Ultrasonic Testing

MAS – Multi-Agent Systems

MAS – Manufacturability Analysis Systems

MAS(2) – Integraged modelling and simulation based life cycle evaluation approach for sustainable manufacturing

MEMS – Microelectromechanical systems

MHR – Material-Handling Robots

MICE – Mesoscopic Integrated Conformal Electronics

MIT – Massachusetts Institute of Technology

MMN – Metals and Metallic Nanostructure

MNE – Multinational Enterprice

MPR – Material-Processing Robots

MQC – Minimum Quantity Cooling

MQL – Minimum Quantity Lubrication

MSI – Manufacturing Sustainability Index

NBC – Nanobiocatalyst

NDE – Non-destructive Evaluation

NDT – Non-destructive Testing

NF – Nanofibre

OEM – Original Equipment Manufacturer

OLP – Off-Line robot Programming

PCB – Printed Circuit Board

PCE – Product Configuration Effectiveness

PCI – Product Configuration Intelligence

PLC – Powerline Communication

PLM – Product Lifecycle Management

POD – Probability of Detection

PPR – Product – Process – Resource structure

PSS – Product Service Systems

PV – Photovoltaic

QFP – Quad Flat Package

RC – Rapid Casting

R&D – Research and development

RF – Radio Frequency

RFID – Radio Frequency Identification

ROI – Return On Investment

SCM – Supply Chain Management

SD – Screw Drives

SGC – Solid Ground Curing

SiP – System in Package

SLA – Stereolithography

SLCM – Stereolithographic Ceramic Manufacturing

SLM – Selective Laser Melting

SLS – Selective Laser Sintering

SME – Small and Medium-Sized Enterprise

SOI – Silicon On Insulator

TCE – Thermal Coefficient of Expansions

TLM – Through Life Management

TRL – Technology Readiness Level

UC Berkley – University of California, Berkeley

US – United States of America

USP – Unique Selling Proposition

VAT – Value Added Tax

VLSI – Very-Large-Scale Integration

VR – Virtual Reality

WEEE – Waste Electrical and Electronic Equipment

WoS – Web of Science

Figures

Tables

1 Introduction

1.1 WP2 – Analysis of main drivers of and barriers to for the uptake of advanced manufacturing by EU industry

Starting from results of the WP1 in terms of diffusion and the impacts of AMT, in this work package we are collecting and analysing new company level information on factors affecting the uptake of advanced manufacturing by EU industry (see Figure 1). The focus is on understanding what and how internal and external drivers and barriers have affected decisions to implement or not to implement AMT, and what the readiness factors are affecting future decisions. This information is going to be transformed into guidelines in WP3 for further policy making.

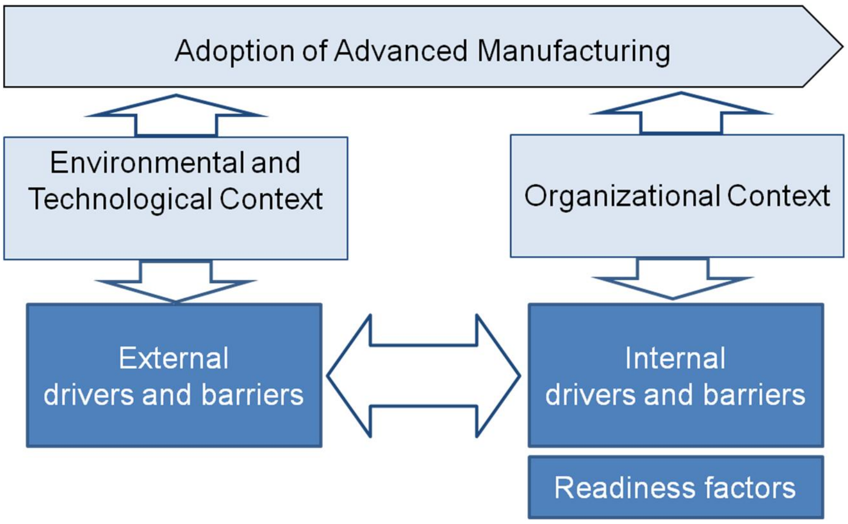


Figure 1. Framework for the study in WP2

1.2 Objectives

The objective of work package 2 is to identify and analyse the drivers of and barriers to the uptake of advanced manufacturing products and technologies by companies. First, we focus on the drivers of embracing advanced manufacturing products and technology. Next, we look at barriers and identify any specific needs for developing support services that European SMEs might need so as to overcome these internal barriers. Finally, we will analyse the readiness of companies to adopt advanced manufacturing as well as possible medium- and long-term consequences of integrating advanced manufacturing such as organizational changes, extra staff training and the change of culture as well as business practices.

1.3 Methodology

The analysis in work package 2 is performed in four phases (see Figure 2). In this deliverable we focus on the first two phases; the literature study and the case study. Firstly, in the literature study we have defined what technologies can be considered as AMT. We have identified drivers of and barriers to investment in advanced manufacturing technology based on prior studies; we describe the advancing and regressing elements in the innovation system development, and we identify good practices and services provided to SMEs in some EU Member States.

Secondly, the results of the literature study form the basis for semi-structured interviews in 10–15 exploratory case studies. We have used interviews in case companies to broaden our understanding of causal relations and to identify factors and variables not known in advance. The cases are chosen from a broad range of industries, regions and technologies in order to acquire an understanding of which drivers have enabled leading companies to invest in advanced manufacturing technology, and what barriers have restricted them from investing more. In this deliverable, we report initial finding from the case studies performed up until February 12th 2016. This gives an understanding of how the case studies are carried out and what type of information we can retrieve from this information. The final results of all case studies will be reported in a later deliverable.

The most important barriers and drivers identified on the bases of the literature study and case studies will help in setting up the survey questionnaire in task 3. An online survey addressing at least 2,500 European companies will be conducted. This survey will be backed up by phone calls in order to obtain at least a 20 % response to the questionnaire. Our research methodology for the study is depicted in the figure below.

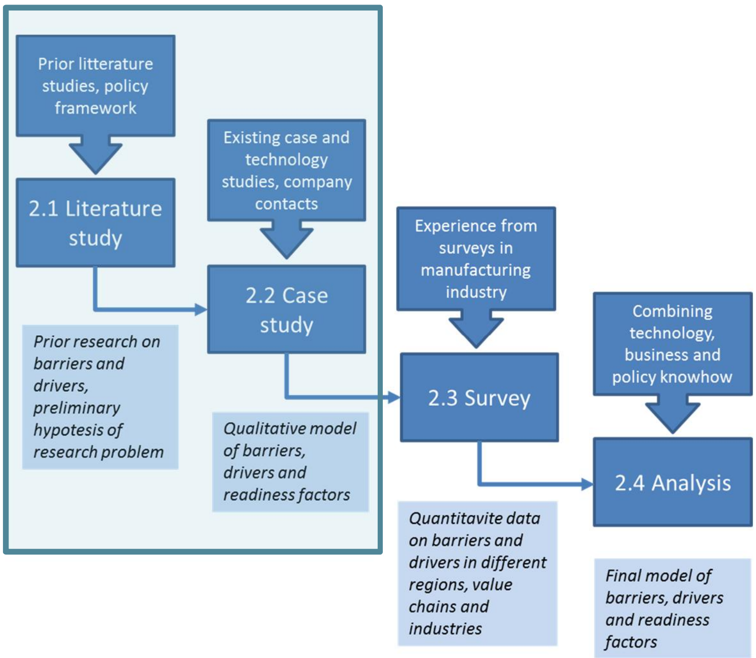


Figure 2. Focus of the report as part of WP2

1.4 Task 2.1: Literature review

The main purpose of the literature review is to provide a starting point for the empirical study identifying and analysing drivers of and barriers to EU companies adopting advanced manufacturing. With this aim we have gathered information from literature thereby highlighting various perspectives of the recent research on AMT.

We have taken stock of the literature in peer-reviewed journals. For this we will use the scientific database Web of Science (WoS) provided by Thompson Reuters as citation data-bases containing information on internationally published articles. WoS is relevant for this purpose because it represents a highly interdisciplinary and comprehensive citation resource providing articles from more than 10 000 journals. In addition to WoS the data base Scopus will also be used for the review. It contains information on 21 000 titles from more than 5 000 international publishers, and includes conference papers which could be used as an important source of results of applied studies. This also contains partly so-called grey literature, such as reports or studies carried out by governmental institutions, research institutions, consulting companies or industry-related associations

The result of this task is an overview of AMT (see Chapter 2.1-2.4), and related drivers and barriers (see Chapter 3 and in more detail Annex I).

1.5 Task 2.2: Case Studies

For an in-depth evaluation of drivers and barriers of adopting AMT, 15 case studies will be conducted into SMEs and large companies (with fewer than 2 000 employees), covering a broad range of manufacturing sectors in five regions of Europe. These case studies will validate and further explore the technologies selected in WP1 as well as the drivers and barriers identified in task 2.1. In this deliverable, we focus on the analysis of the first set of case analyses in order to test and evaluate the information we can derive from the case study methodology.

Case studies are favourable when "how" or "why" questions are being asked. Yin (2003) suggests that case studies are favourable when contemporary events are investigated and when behaviour cannot be controlled. In this project, not all of the potentially important variables are known in advance. Hence, we have defined a research design that allows for an open mind within a given research range. Moreover, the company we study cannot be separated from its context, and hence, case-specific conditions are taken into account.

Our case study design is based on that of Qualitative Causal Analysis (Huberman and Miles, 1994). Huberman and Miles consider qualitative analysis to be a very powerful method to assess causality. Qualitative analysis is unrelentingly local, and deals well with the complex network of events and processes in a situation. The case studies are carried out with the help of semi-structured interview guidelines, which allow open answers to questions without fixed categories (Mayer, 2006). By doing this, a more thorough insight into the business perspective of barriers and drivers is possible, and critical aspects, which previously might have been overseen, find their way into the considerations of later work packages.

In the initial phase of the ManStu project, we have conducted 7 interviews in 7 companies in 5 countries. In this report, we summarise the initial case findings based on these cases.

2 Literature study

The literature review focuses on two separate questions: 1) what are AMT, and 2) what are the drivers of and barriers to investment in AMT. In this chapter, the focus will be on the first of these two. Here we first describe how advanced manufacturing technology has been defined in previous studies, how the Key Enabling Technologies are related to these technologies, and how the literature search was set up to find more information on the topic. More detailed information on AMT and their drivers and barriers can be found in Annex I: Drivers of and barriers to AMT – Literature study. At the end of this chapter we present a generalized list of AMT.

2.1 What is Advanced Manufacturing?

2.1.1 Definitions of Advanced Manufacturing

The Science and Technology Institute (2010) present a set of definitions of advanced manufacturing proposed by experts. These definitions are:

- *"New Manufacturing Industries.* Based on what is being produced, this definition focuses on new and emerging industries such as aerospace and bio-manufacturing (the manufacturing arm of the biotechnology industry) as opposed to "traditional" manufacturing such as steel, automotive or machinery.
- *Use of New Methods for Manufacturing.* This definition includes industries that develop newer and better products through the use of advanced production technologies. Under this definition, advanced manufacturers use computer, high precision and information technology combined with a skilled workforce.
- *Sustaining the Cutting Edge.* Another definition offered by some experts is the rapid transfer of science and technology into manufacturing processes and products. Today's digital economy allows competitors to quickly adopt new products, replacing the current cutting-edge technology. Therefore, to remain a front-runner, the time from research and development to production must be reduced.
- *Manufacturing Frontier.* This definition contrasts with those that distinguish between traditional and advanced manufacturing, noting that technological advancements and innovation take place in both well-established and emerging industries and apply to both existing and new products. This viewpoint presents a dynamic non-definition as businesses strive to achieve and maintain a competitive advantage. As the "frontier" continually changes, so does what comprises advanced manufacturing.

Taking into account the definitions above, the 2011 report to the President, Ensuring American Leadership in Advanced Manufacturing, and the 2012 report, Capturing Domestic Competitive Advantage in Advanced Manufacturing, prepared by Presidents' Council of Advisors on Science and Technology offer a comprehensive definition"[1] (Executive Office of the President, 2011; 2012):

"Advanced Manufacturing is a family of activities that:

- depend on the use and coordination of information, automation, computation, software, sensing, and networking; and/or
- make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry and biology.

This involves both new ways of manufacturing existing products, and especially the manufacture of new products emerging from new advanced technologies."[2]

In a similar vein, the EU Task Force for Advanced Manufacturing Technologies for Clean Production defines Advanced Manufacturing to "include production activities able to improve production speed, productivity, energy and materials consumption, operating precision, waste, pollution management and enabling resource-efficient and low emission production" (European Commission, 2016a).[3]

2.1.2 What is the difference between typical and advanced manufacturing?

In today's rapidly shifting global economy, there is not any single definition about manufacturing. The chart below (Table 1) "summarizes how the manufacturing environment is changing in key areas" (Camoin Associates, 2011)[4].

[1] White Papers on Advanced Manufacturing Questions, Science and Technology Institute, 2010. http://www.expansionsolutionsmagazine.com/industry_articles/view/9067/understanding_advanced_manufacturing

[2] Executive Office of the President. 2011. Report to the President on Ensuring American Leadership in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2011, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf ref 26.4.2016, page ii [30]

[3] European Commission. 2016a. EU Task Force for Advanced Manufacturing Technologies for Clean Production http://ec.europa.eu/growth/industry/innovation/advanced-manufacturing/index_en.htm ref 26.4.2016, [26]

[4] Camoin Associates. 2011. Research by Camoin Associates, Presentation by Robert M. Ady to the International Economic Development Council, September 18, 2011 http://www.expansionsolutionsmagazine.com/industry_articles/view/9067/understanding_advanced_manufacturing ref. 12.5.2016, [7]

Table 1. Characteristics of advanced manufacturing (source: Camoin Associates, 2011)[5]

Conventional Manufacturing	Characteristic	Advanced Manufacturing
Mass production	Production Strategy	Customization and customer focused
Hierarchical	Organisational structure	Flat, open flow or information
Abundant labour supply	Labour Supply Criteria	Skilled/Technical labour available
Unskilled and semi-skilled	Skills Requirement	Semi-skilled and technical skills
On-the-job training, High-school Vocational school	Education	Technical degree from college/university
3 semi-skilled workers for every skilled worker	Labour Force	4 skilled workers for every semi-skilled worker
Casting, welding, moulding, brazing, machining, etc.	Production Technology	Additive and rapid manufacturing: 3-D printing, Powder bed, Material deposition, etc.
Investment into production	R&D/Innovation	Re-invest revenues into R&D
Low cost	Energy	Low-cost, high-dependable
Space	Infrastructure Requirements	IT/digital infrastructure
Highway and/or rail accessibility	Logistics	Global supply-chain management

Due to high wages and strong growth prospects, advanced manufacturing is interesting to economic developers and policy makers. "Over the next ten years the advanced manufacturing sector is expected to grow five times faster than the manufacturing industry as a whole. Advanced manufacturers can range from large operations with hundreds of employees to operations that employ only a few highly-skilled people"[6] (Executive Office of the President, 2011).

2.2 What are KETs and why are they important?

The Key Enabling Technologies (KETs) is a set of advanced manufacturing technologies defined by the European Commission. They have a vital role in European Commission's technology strategy. They "are a group of six technologies that have a wide range of product applications such as developing low carbon energy technologies, improving energy and resource efficiency, and creating new medical products. They have a huge potential to fuel economic growth and provide jobs" (European Commission, 2016b)[7].

[5] Camoin Associates. 2011. Research by Camoin Associates, Presentation by Robert M. Ady to the International Economic Development Council, September 18, 2011 http://www.expansionsolutionsmagazine.com/industry_articles/view/9067/understanding_advanced_manufacturing ref. 12.5.2016.

[6] Executive Office of the President. 2011. Report to the President on Ensuring American Leadership in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2011, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf ref 26.4.2016, page ii [30]

[7] European Commission. 2016b. What are KETs and why are they important? http://ec.europa.eu/growth/industry/key-enabling-technologies/description/index_en.htm ref 26.4.2016, [27]

According to the European Commission's definition "KETs comprise micro and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies. The 2009 Communication on KETs describes these further. They provide the basis for innovation in a wide range of industries such as automotive, food, chemicals, electronics, energy, pharmaceuticals, construction and telecommunications. They can be used in emerging and traditional sectors" (European Commission, 2016b).[8]

KETs are prioritised by the European Commision because they are seen as potential means for industrial growth. "The European Strategy for KETs aims to accelerate the rate of exploitation of KETs in the EU and to reverse the decline in manufacturing to stimulate growth and jobs" (European Commission, 2016b).[9]

2.2.1 The Economic Importance of KETS

According to the European Commission, the "economic impact of KETs is considerable. The global market for KETs is estimated to be more than EUR 1 trillion by 2015. Exports from EU countries account for 23 % of world exports in KETs-based products. Also, KETs have huge potential for growth and employment. According to the European Competitiveness Report 2013, depending on KETs, growth potentials of 10–20 % per year can be expected over the coming years. For particular submarkets, the growth potential is even larger" (European Commission, 2016b).[10]

The Commission states that "countries and regions that fully exploit KETs will be at the forefront of advanced and sustainable economies. KETs deployment will contribute to achieving re-industrialisation, energy, and climate change targets simultaneously, making them compatible and reinforcing their impact on growth and job creation" (European Commission, 2016b).[11]

2.2.2 Identifying key enabling technologies

According to a Commission's recent report, "several Member States have started to identify enabling technologies relevant to their future competitiveness and prosperity, and to target their R&D spending accordingly" (European Commission, 2009c).[12] "However, there are differences between Member States on what should be regarded as KETs. This might be explained

[8] European Commission. 2016b. What are KETs and why are they important? http://ec.europa.eu/growth/industry/key-enabling-technologies/description/index_en.htm ref 26.4.2016, .

[9] ibidem.

[10] ibidem.

[11] ibidem.

[12] European Commission. 2009c. Preparing for our future: Developing a common strategy for key enabling technologies in the EU. Staff Working Paper (SEC (2009) 1257). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN ref 26.4.2016, page 3 [24]

by the strengths and limits of their research and industrial landscapes"[13] (European Commission, 2009b). According to the 2009 Science, Technology and Competitiveness report, leading economies such as China, Japan and the US are focusing on biotechnology, ICT and nanotechnology also (European Commission, 2009d). "Within ICT, specific fields such as micro- and nanoelectronics and photonics deserve immediate policy actions, given the situation of the EU industry in global competition and the challenges stemming from the economic crisis."[14][15] The EU has offered cooperation to international partners on carbon capture and storage systems (CCS) and hence, European manufacturing companies must "possess the necessary, affordable technologies" (European Commission, 2009b).[16]

"Based on current global research and market trends, the following could be regarded as the most strategically relevant KETs, given their economic potential, contribution to solving societal challenges and knowledge intensity" (European Commission, 2009b):[17]

- "Nanotechnology holds the promise of leading to the development of smart nano and micro devices and systems and to radical breakthroughs in vital fields such as healthcare, energy, environment and manufacturing;
- Micro- and nanoelectronics, including semiconductors, are essential for all goods and services which need intelligent control in sectors as diverse as automotive and transportation, aeronautics and space. Smart industrial control systems permit more efficient management of electricity generation, storage, transport and consumption through intelligent electrical grids and devices;
- Photonics is a multidisciplinary domain dealing with light, encompassing its generation, detection and management. Among other things, it provides the technological basis for the economic conversion of sunlight to electricity which is important for the production of renewable energy, and a variety of electronic components and equipment such as photodiodes, LEDs and lasers;
- Advanced materials offer major improvements in a wide variety of different fields, e.g. in aerospace, transport, building and health care. They facilitate recycling, lowering the

[13] European Commission. 2009b. Preparing for our future: Developing a common strategy for key enabling technologies in the EU COM (2009) 1257. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN, page 3 [23]

[14] Ibidem

[15] Other important ICT areas, such as software and communication technologies, including the development of the Future Internet or high-speed broadband are supported by separate EU initiatives and are therefore not in the focus of this Communication (see European Commission, 2009a)

[16] European Commission. 2009b. Preparing for our future: Developing a common strategy for key enabling technologies in the EU COM (2009) 1257. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN, page 3 [23]

[17] Idem, page 4 [23]

carbon footprint and energy demands as well as limiting the need for raw materials that are scarce in Europe;

- Biotechnology brings cleaner and sustainable process alternatives for industrial and agri-food operations. It will, for example, allow the progressive replacement of non-renewable materials currently used in various industries with renewable resources; however, the scope of applications is just at the beginning"[18].

Advanced manufacturing systems are expected to produce high value goods and related services. This is "especially relevant in capital-intensive industries with complex assembly methods, such as the production and assembly of modern aircraft, which involves the whole spectrum of manufacturing technologies from the simulation and programming of robotic assembly lines to reducing energy and materials consumption. Given the rapid development in science and research, the above technologies may rapidly become global in the years to come and other technologies may emerge" (European Commission, 2009b).[19]

2.3 Search strategy for advanced manufacturing technologies

We combine the definition set up by the US President's Council of Advisors on Science and Technology – quoted above in Section 2.1 – with our Technical Proposal distinguishing AMT by: performance in technical and economic terms (high performance), performance related to efficient use of resources (sustainability) and manufacturing technologies enabled by ICT as proposed by the EU Task Force for Advanced Manufacturing Technologies for Clean Production (European Commission, 2016a):

- "Sustainable manufacturing technologies: Technologies to increase manufacturing efficiency in the use of energy and materials and drastically reduce emissions (e.g. process control technologies, efficient motor systems, efficient separation technologies, novel sustainable process inputs, product lifecycle management systems)

- ICT-enabled intelligent manufacturing: Integrating digital technologies into production processes (e.g. smart factories).

[18] European Commission. 2009b. Preparing for our future: Developing a common strategy for key enabling technologies in the EU COM (2009) 1257. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN, page 3 [23]

[19] Idem, page 5 [23]

- High performance manufacturing: Systems combining flexibility, precision and zero-defect mechanisms (e.g. high precision machine tools, advanced sensors, 3D printers)."[20]

It follows that, in our literature study, we will have the following search strategy:

Search term	hits 2000-
"advanced manufacturing"	1 168
"sustainable manufacturing" OR (sustainability AND manufacturing)	2 130
manufacturing AND ("digital technologies" OR "big data" OR "Internet of Things" OR "Industrial Internet" OR "Cyber-Physical Systems" OR "Product Lifecycle Management" OR "supply chain management" OR "enterprise resource planning" OR "manufacturing resource planning")	2 731
"high-performance manufacturing" OR "additive manufacturing" OR "micro-manufacturing" OR (manufacturing AND "industrial robot*")	2 443

We then follow with Key Enabling Technologies (KETs) and complement the search with the remaining five technologies as follows:

Search term	hits 2000-
nanotechnology AND manufacturing	1 131
(microelectronics OR nanoelectronics) AND manufacturing	840
photonics AND manufacturing	378
"advanced materials" AND manufacturing	247
biotechnology AND manufacturing	751
all together	11 278

2.4 Updated list of AMT

The literature study in Annex I is a comprehensive study of AMT, and drivers and barriers related to their implementation. It gives an understanding of how wide and diverse this topic is in reality. In this chapter, we have grouped these specific technologies into broader groups of AMT. To gain a full understanding of the width of this topic we recommend that the reader takes time to read Annex I to this report. Reading this text also helps the reader to understand the summary on drivers and barriers in Chapter 3.

[20] European Commission. 2016a. EU Task Force for Advanced Manufacturing Technologies for Clean Production http://ec.europa.eu/growth/industry/innovation/advanced-manufacturing/index_en.htm ref 26.4.2016, page 6 [26]

Based on the findings in WP1 and on the literature study, we have compiled an updated list of AMT in Table 2. This list will be used in the company survey to define the main groups of AMT.

Table 2. List of AMT

1.	High Performance Manufacturing Technologies
-	Industrial robots/ handling systems
-	Automated Warehouse Management Systems
-	Technologies for safe human-machine cooperation, improved usability
-	Manufacturing micromechanical components
-	Additive manufacturing
-	Photonics (other than additive)
-	Processes specific to Advanced Materials
-	Nano-manufacturing
-	Processes for bio-manufacturing
-	High-performance machinery
-	Modular and adaptable (interoperable) machines
-	Cutting and machining techniques for rapid prototyping equipment manufacture, Rapid time-to-market enabling technologies
-	Self-adaptive production lines
-	Printed electronics/roll-to-roll processes
-	Silicon-on-chip, heterogeneous circuits, and embedded systems, Integrated photonic circuits
-	Microelectromechanical systems (MEMS) and sensor devices
-	Nanoelectronics materials and patterning, Nanoimprint (process and equipment), Precision manufacturing and metrology
-	other [open text field]
2.	ICT-Enabled Technologies
-	VR / simulation in production reconfiguration
-	VR / simulation in product design, Digital design technologies, Design platforms for modular, adaptable manufacturing
-	Supply chain management with suppliers/customers, Network-centric production, Optimization of production networks
-	Product Lifecycle Management Systems, Product Data Management Systems
-	Enterprise Resource Planning
-	Technologies that depend on the use and coordination of information, automation, computation, software, sensing, and networking
-	Mass customization (three-dimensional printing, direct digital manufacturing)
-	Cyber-physical (production) systems, intelligent components
-	Cloud manufacturing
-	other [open text field]

3.	Sustainable Manufacturing Technologies
-	Dry processing/minimum lubrication
-	Recuperation of kinetic and process energy
-	Control system for shut down of machines
-	Combined cold, heat and power (Bi-/Trigeneration)
-	Recycling and waste/disposal management technologies
-	Use of renewable technologies and processes, Low power electronics, Li-ion and thin film battery technology, Photovoltaic cells
-	(Advanced) materials research for green manufacturing, Materials modelling and simulation
-	Alternately fuelled vehicles, Fuel cell technology
-	Green manufacturing and “low carbon” technologies, Green design/ Eco-design
-	Product Life Cycle optimization, Service Life optimization
-	other [open text field]

3 Drivers of and barriers to AMT investment – summary of literature study results

In the US, Advanced Manufacturing is defined as "a family of activities that i) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or ii) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry and biology. This involves both new ways of manufacturing existing products, and especially the manufacture of new products emerging from new advanced technologies."[21] (Executive Office of the President, 2011). In a similar vein, the EU Task Force for Advanced Manufacturing Technologies for Clean Production defines Advanced Manufacturing as it to include production activities able to improve production speed, productivity, energy and materials consumption, operating precision, waste, pollution management and enabling resource-efficient and low emission production"[22] (European Commission, 2016a).

A vital element in European Commission's technology strategy are Key Enabling Technologies (KETs) that "are a group of six technologies that have a wide range of product applications such as developing low carbon energy technologies, improving energy and resource efficiency, and creating new medical products."[23] "KETs comprise micro and nano electronics, nanotechnology, industrial biotechnology, advanced materials, photonics and advanced manufacturing technologies."[24] "They provide the basis for innovation in a wide range of industries such as automotive, food, chemicals, electronics, energy, pharmaceuticals, construction, and telecommunications. They can be used in emerging and traditional sectors"[25] (European Commission, 2016b).

KETs are expected to help European industries grow, and hence," are a priority for European industrial policy. The European Strategy for KETs aims "to accelerate the rate of uptake of KETs in the EU and to reverse the decline in manufacturing so as to stimulate growth and jobs"[26] (European Commission, 2016b).

---

[21] Executive Office of the President. 2011. Report to the President on Ensuring American Leadership in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2011, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf ref 26.4.2016, page ii [30]

[22] European Commission. 2016a. EU Task Force for Advanced Manufacturing Technologies for Clean Production http://ec.europa.eu/growth/industry/innovation/advanced-manufacturing/index_en.htm ref 26.4.2016, [26]

[23] European Commission. 2016b. What are KETs and why are they important? http://ec.europa.eu/growth/industry/key-enabling-technologies/description/index_en.htm ref 26.4.2016, [27]

[24] Ibidem.

[25] Ibidem.

[26] Ibidem.

We combine the Advanced Manufacturing definition with our Technical Proposal distinguishing AMT by: performance in technical and economic terms (high performance), performance related to the efficient use of resources (sustainability) and manufacturing technologies enabled by ICT as proposed by the aforementioned Task Force of AM (European Commission, 2016a):

- "ICT-enabled intelligent manufacturing: Integrating digital technologies into production processes (e.g. smart factories).
- High performance manufacturing: Systems combining flexibility, precision and zero-defect mechanisms (e.g. high precision machine tools, advanced sensors, 3D printers).
- Sustainable manufacturing technologies: Technologies to increase manufacturing efficiency in the use of energy and materials and drastically reduce emissions (e.g. process control technologies, efficient motor systems, efficient separation technologies, novel sustainable process inputs, product lifecycle management systems)"[27]

Our literature search produced 11 278 scientific and business articles. We limited ourselves to articles that have been published from the year 2000 onwards.

The adoption process of advanced manufacturing technologies is influenced by different drivers and barriers which can be categorized in three critical groups: technology-specific, company-specific and company-external factors, thereby representing the technological, organizational and environmental contexts of adoption (see Tornatzky and Fleischer, 1990).

- The technological context refers to the nature of the technology adopted. The adoption of a new advanced technology depends on the recognition of the perceived benefits of using it by adopters, e.g. in terms of the profitability and maturity of the technology, the perceived risks and the compatibility with the production structure of the company.
- The organizational context refers to the descriptive characteristics of the (potential) adopter. It not only includes the structural variables such as its size or sector affiliation, but also the existing know-how, the available technical, financial and human resources, innovation strategy and organizational characteristics.
- The company's environmental context refers to the arena in which it conducts its business, and includes the actors in the value chain such as suppliers, customers, as well as competitors, research institutions, business associations, politics, etc. These actors represent information and knowledge sources for new technologies, and can provide the company with necessary financial and human resources, thereby reducing the risk of concomitant adoption.

[27] European Commission. 2016a. EU Task Force for Advanced Manufacturing Technologies for Clean Production http://ec.europa.eu/growth/industry/innovation/advanced-manufacturing/index_en.htm ref 26.4.2016, [26]

We summarize our findings of the related drivers and barriers for the implementation in advanced manufacturing in the aforementioned three fields as follows.

3.1 Barriers to and drivers of ICT-enabled intelligent manufacturing

The adoption process of AMT in SMEs is influenced by different drivers and barriers, which can be categorized into three critical groups: technology-specific, company-specific and company-external factors, thereby representing the technological, organizational and environmental contexts of adoption (see Figure 3).

- The technological context refers to the nature of the technology adopted. However, it describes not only the set of external available technologies to the firm, but also its internal current practices and equipment. Hence, the adoption of a new advanced technology depends on the recognition of the perceived benefits of using it by adopters, e.g. in terms of the profitability and maturity of the technology, the perceived risks and the compatibility with the production structure of the company.
- The organizational context refers to the descriptive characteristics of the (potential) adopter. It includes not only the structural variables such as its size or sector affiliation, but also the existing know-how, the available technical, financial and human resources, innovation strategy and organizational characteristics. More-over, it refers to the cultural and manufacturing strategy of the company.
- The company's environmental context refers to the arena in which it conducts its business and includes the actors in the value chain such as suppliers, customers, as well as competitors, research institutions, business associations, politics, etc. These external factors can influence the adoption of new technologies through regulatory conditions or customer demand. Moreover, these actors represent information and knowledge sources for new technologies and can provide the company with the necessary financial and human resources, thereby reducing the risk of concomitant adoption.

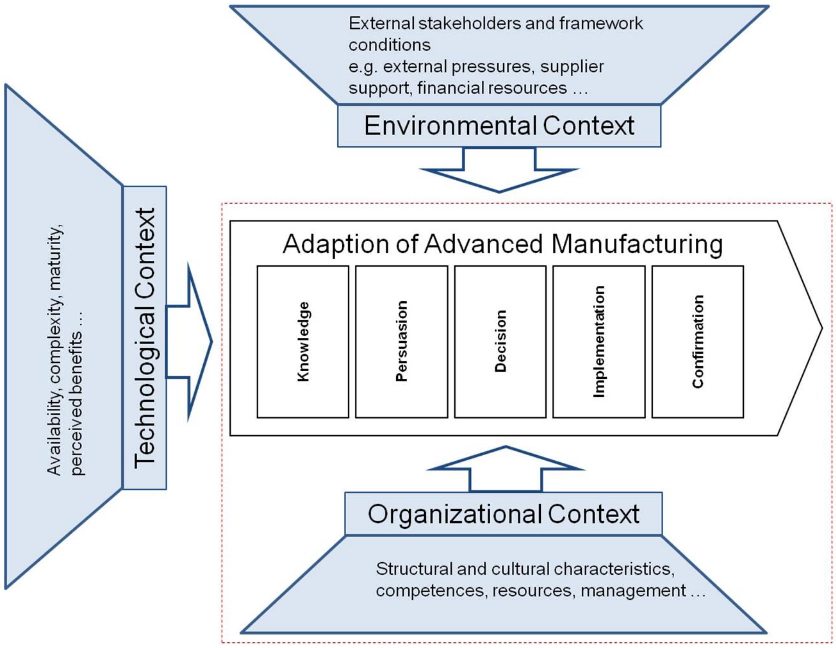


Figure 3. Contextual framework. Source: Tornatzky and Fleischer (1990), Rogers (2003), del Rio Gonzalesz (2005), Dar-banhosseiniamirkhiz and Ismail (2012)

This framework has been used as a basis for the analysis of the drivers and barriers in the literature study.

3.1.1 Financial and General Management Perspective

Within the Environmental Context, difficulties are caused by the shift of power and change of roles within the supply chain as it moves into the arena of digital content delivery (Nath et al, 2008). Similarly, it can be difficult to manage the challenges (and opportunities) of context, that is, the different nations' political, regulatory, judicial, tax and labour environments (Isenberg, 2008). In addition, as drivers, nations may have tax policies supporting innovation, including incentives for R&D and tax benefits for "advanced manufacturing" (Graetz and Doud, 2013).

In the Organizational Context, challenges include top management support, organisational motivation and the extent of progress supervision and policy, structure and operating process compatibility. For example, difficulties may relate to managing the expectations of non-technologically driven management and to balancing the development of the strategic goals with pressures for commercial output. The optimization of organization processes rather than individual benefits poses challenging culture change management issues, including operation strategy, organizational culture, organizational structure, implementation practices and strategic consensus (Rangan et al, 2005). Also, it is claimed that there is an increased "gap between the competences needed by industry and those provided by the universities' curricula"[28] (Secundo et al, 2013).

On the other hand, "the significance of intangible resources for business success has increased and may in some cases already be assessed as higher than the impact of tangible resources"[29] (Kohl et al, 2014). Hence, there is room for managerial ingenuity and innovation management. ICT-enabled intelligent manufacturing makes it possible to improve supply chain visibility, to conduct experiments and what-if analyses, and to improve the understanding of the real system. This improves communication within and between organizations in the supply chain. For example, physical product, information systems and financial flows can be closely aligned with each other throughout the supply chain incorporating the core company, its customers, suppliers and banks. The sharing of financial data as part of a cooperative strategy generated cost savings in areas such as foreign exchange and cash balances (Blackman et al, 2013).

Within the Technological Context, it can be difficult for the management to evaluate investments in information systems: benefits may be intangible and non-financial, and indirect project costs further complicate the justification process. Similarly, it can be difficult to establish performance metrics and make benefit-cost analysis (Irani, 2002). For example, balancing the benefits of global sourcing strategies' cost-effectiveness against the limitations of off-shore productions can be a challenging task (Nath et al, 2008). On the other hand, ICT-enabled intelligent manufacturing is claimed to produce the following benefits: reduced operating and admin costs, reduced stock levels, increased turnover, reduced IT operating costs and reduced quality costs.

3.1.2 Customer Perspective

One driver of ICT-enabled intelligent manufacturing is that it makes it possible to respond quickly and effectively to market demands. "Close relationships with suppliers are claimed to leave room for special orders in unique times of high demand, helping satisfy customer expectations."[30] Moreover, ICT-enabled intelligent manufacturing gives a customer greater control over the processing of an order by integrating technologies which allow for greater tracking of the order. Similarly, it makes it possible for the customer to dynamically influence the way the order is produced, stored or transported (Fawcett et al, 2008).

---

[28] Secundo, G; Passiante, G; Romano, A; Moliterni, P. 2013. Developing the Next Generation of Engineers for Intelligent and Sustainable Manufacturing: A Case Study. Int. J. Eng. Educ, vol. 29, 1, page 248 [70]

[29] Kohl, H; Galeitzke, M; Steinhofel, E; Orth, R. 2014. Strategic Intellectual Capital Management as a Driver of Organisational Innovation. IFKAD 2014: 9th International Forum on Knowledge Asset Dynamics: Knowledge and Management Models for Sustainable Growth, Jun 11–13, 2014, page 1481 [45]

[30] Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1,, page 37 [32]

3.1.3 Operations Perspective

In the Environmental Context, an important driver of the implementation of intelligent manufacturing systems is the national culture and government/corporate policies. However, there are also a number of barriers. Within the Organizational Context, the barriers "include difficulty in accessing data from partners in the supply chain, difficulty in accessing data on a higher level of granularity and difficulty in retrieving data from other information systems"[31] (Hilletofth and Lattila, 2012). "Inter-firm rivalry" might even occur that follows "a misalignment of motives and behaviours among allying partners within the strategic supply chain"[32] (Fawcett et al, 2008).

Even within ICT-enabled intelligent manufacturing, software alone cannot directly cause actions in the real world without connections to physical technologies such as actuators or transportation systems, or through interfaces to human operators (McFarlane et al, 2013). Companies "report difficulty in finding skilled labour, especially with industry-specific experience"[33] (Cormia et al, 2013). Moreover, unanticipated dynamic interactions due to repeated use or misuse of components makes it "increasingly difficult for plant personnel to anticipate, diagnose and control serious abnormal events in a timely manner,"[34] and human operators tend to make erroneous decisions (Venkatasubramanian, 2005). On the other hand, ICT-enabled intelligent manufacturing is expected to increase the user friendliness of information systems (IS) and adherence to best practice work patterns, organisational learning, and hence, the effectiveness of employees.

Within the Technological Context, barriers may occur because of the isolation of companies' IT systems; their communication, cooperation and integration may result in more and more overheads and quickly becomes unmanageable. Hence, the stability of operations of highly distributed systems must be considered. It can be difficult to demonstrate that an intelligent product environment can be deployed with industrial scale information systems to: specify open, standard, user-friendly and widely-accepted interfaces, specify what information is gathered, stored and distributed and how it is managed during the product's lifecycle (McFarlane et al, 2013). A barrier to the implementation of an intelligent manufacturing system can be the difficulty of analysing the real-time production performance for the shop-floor (Zhang

[31] Hilletofth, P; Lättilä, L. 2012. Agent based decision support in the supply chain context. Ind. Manage. Data Syst., vol. 112, Sep 8, page 1217 [38]

[32] Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, page 35 [32]

[33] Cormia, RD; Oye, MM; Nguyen, A; Skiver, D; Shi, M; Torres, Y. 2014. Integrating Electron Microscopy into Nanoscience and Materials Engineering Programs. SCANNING MICROSCOPIES 2014, SEP 16–18, 2014, page 92360N-1 [14]

[34] Venkatasubramanian, V. 2005. Prognostic and diagnostic monitoring of complex systems for product lifecycle management: Challenges and opportunities. Comput. Chem. Eng., vol. 29, May 15, page 1253 [79]

et al, 2014). In a more general setting, traditional six-sigma techniques show major limitations to highly changeable production contexts, characterized by small batch productions, customized, or even one-of-a-kind products"[35] (Ulewicz et al, 2014).

On the other hand, within the Technological Context, ICT-enabled intelligent manufacturing is expected to improve manufacturing operations in a number of ways, to: optimize resources, reduce manufacturing cycle times, reduce data processing time, increase inventory turns, improve accuracy and timeliness of information, enhance internal information sharing, reduce manufacturing lead times and increase integration of applications. These are claimed to lead to improved decision-making and improved vendor performance.

There are a number of ways Enterprise Resource Planning (ERP) can improve decision-making. Chand et al. (2005) found that ERP systems can be used to inform affected parties across the value-chain, thereby improving decision-making at all levels. The case company's managers noted that the surprise benefit of the ERP system implementation was the improved information visibility across the entire value-chain. Indeed, ERP systems are expected enhance decision-making by providing accurate and timely enterprise-wide information. When implementing ERP systems, companies try to reduce data redundancy and inconsistency through a central database of corporate information. Moreover, employees have access to current information for decision-making (Poston and Grabski, 2001). Spathis and Constantinides (2003) emphasize the linkage between ERP systems and companies' business operations. Their evidence reinforces the argument that ERP systems have been successful for the business as a whole. That is, the integration of applications, the production of real-time information and particularly information for decision making affect business operations in general. ICT-enabled intelligent manufacturing allows the evaluation of various manufacturability aspects during the design stage and consequently a reduction in the costs and time to market of the designed products (Shukor and Axinte, 2009).

Table 3. Barriers and drivers in ICT-enabled intelligent manufacturing

	Barriers	Drivers
Environmental Context	• Expected shift of power and change of roles within the supply chain as it is digitalized • Difficulty in managing different nations' political, regulatory, judicial, tax and labour environments • Difficulty in evaluating investments in information systems, establishing per-	• Tax policies supporting innovation, for example, incentives for R&D, and tax benefits for "advanced manufacturing" • Promises of enhanced company performance by improved decision-making, reduced operating and administrative costs and enhanced business processes • Gives a customer greater control over the

[35] Ulewicz, S; Schutz, D; Vogel-Heuser, B. 2014. Integration of Distributed Hybrid Multi-Agent Systems into an Industrial IT Environment. 2014 12TH IEEE INTERNATIONAL CONFERENCE ON INDUSTRIAL INFORMATICS (INDIN), JUL 27–30, 2014, page 519 [77]

	formance metrics and making for benefit-cost analysis	processing of an order; allows the customer to dynamically influence the way the order is produced, stored or transported
Organizational Context	• Difficulties in managing the expectations of non-technologically driven management • Difficulties in balancing the development of the strategic goals with pressures for commercial output • Difficulty in managing collaborative workflows, increased inter-firm rivalry due to a misalignment of motives and behaviours among allying partners • Challenging culture change management issues, resistance to change • Difficulty in finding skilled labour • Difficulty in developing innovative learning approaches and strategy to incentivise the development of competence	• Significance of intangible resources for business success has increased and may in some cases already be assessed as higher than the impact of tangible resources • Physical product, information systems and financial flows can be closely aligned with each other throughout the supply chain to improve supply chain visibility, to conduct experiments and what-if analyses, to improve the understanding of the real system and the possibility to improve communication • Adherence to best practice work patterns, organisational learning and effectiveness of employees
Technological Context	• Difficulty in demonstrating that an intelligent product environment can be deployed on an industrial scale • Difficulty in accessing and retrieving data from partners and other information systems • Traditional six-sigma techniques show strong limitations in highly changeable production contexts	• Revenue growth fuelled by increased responsiveness occurring at lower costs using fewer assets, by reduced manufacturing cycle times, increased inventory turns, improved accuracy and timeliness of information • Improved ability to respond quickly and effectively to market demands, allows inventory to cycle through to customers faster • Allow the evaluation of various manufacturability aspects during the design stage

3.2 Barriers to and drivers of high performance manufacturing

3.2.1 Financial and General Management Perspective

Within the Organizational Context, potential barriers to the implementation of high performance manufacturing include requirements for advanced planning procedures and user involvement plans, need to improve communication, potentially change company labour policies and to introduce continuous training programmes. Management should take timely action with regard to these (Das, 2001).

Within the Technological Context, the advantages of high performance manufacturing and, hence, its drivers cover improved process documentation and aspects of quality control, cost minimization and the efficiency improvement. However, there are barriers to the implementation of high performance manufacturing technologies, too. For example, there are challenges in additive manufacturing relate to environment and energy, scale and cost of production and structural performance.

3.2.2 Customer Perspective

Within the Technological Context, laser integration, optical coupling of devices and subsystem assembly still remain the key challenges that need to be further investigated in order to achieve high-yield and to reduce micro and nano manufacturing costs. Similarly, "the integration of micro-components into macro-scale products is non-trivial, conventionally posing difficult questions and compromises in the domains of packaging, interconnection and design:"[36] "system-in-package integration capabilities require thermal management, temperature resistivity and heterogeneous system integration"[37] (Topham and Harrison, 2008; Bechtold, 2009).

However, there are a number of factors that drive developments in micro and nano manufacturing. Typically, these are related to the desire to better meet the customer needs. For example, medical applications need to provide biocompatibility, the highest miniaturization, withstand rough treatment, autoclave sterilization and resistance to harsh environments in order to be applicable (Braun et al, 2012; Sidambe, 2014).

Micro-scale structures operate at higher frequency and save energy. In micro-mechanics, small feature size "structures have low mass and high resonant frequencies, enabling high sensitivity yet robust operation. In micro-fluidics, micro-channels exhibit highly laminar flow, providing the potential for chemistry at molecular scales and the ability to single out and manipulate individual living cells"[38] (Topham and Harrison, 2008). Similarly, monolithic electronics-photonics integration enables the integration of electronics and optics on a single chip, using CMOS manufacturing infrastructure and mature microelectronics fabrication processes, and promises to enable "platforms tailored to a vast array of emerging applications, from optical and acoustic sensing, high-speed signal processing, RF and optical metrology and clocks, through to analogue computation and quantum technology."[39] Coupling the monitoring flexibility offered by photonics technologies with the data transmission flexibility of wireless networking provides opportunities to develop hybrid wireless sensor solutions, incorporating optical sensors into wireless condition monitoring architectures (Bechtold, 2009). This provides versatility, low costs and installation and operational flexibility as well as unique safety and

---

[36] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from in-tegrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, page 1311 [75]

[37] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Techno-logies. 2009 EUROPEAN MICROELECTRONICS AND PACKAGING CONFERENCE (EMPC 2009), VOLS 1 AND 2, JUN 16–18, 2009, page 798 [2]

[38] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from in-tegrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, page 1311 [75]

[39] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Techno-logies. 2009 EUROPEAN MICROELECTRONICS AND PACKAGING CONFERENCE (EMPC 2009), VOLS 1 AND 2, JUN 16–18, 2009, page 798 [2]

reliable operation characteristics in real industrial environments of excessive electromagnetic interference and noise (Emmanouilidis and Riziotis, 2015).

Moreover, there is great “potential of different nano-particles as additives for plastic packaging materials for enhanced humidity resistance/barrier enhancement:”[40] e.g. plastic packaging materials with enhanced humidity resistance increase package reliability during assembly and lifetime without cost increases and with no changes in processing (Braun et al, 2008). On a macro scale, additive manufacturing provides the opportunity for the production of high value custom and limited edition products (Mahamood et al, 2014).

3.2.3 Operations Perspective

Within the Organizational Context, a potential barrier to the introduction of advanced machinery can be the difficulty to manage “the ever-increasing information flow and system complexity of production cells that incorporate equipment from different producers”[41] (Chioreanu et al, 2013). The number of tasks of the same type can be limited because of the size of an SME. Robots do not adapt well to dynamic environments, do not offer rich human-robot interaction and are not simple for end-users to programme (Heyer, 2010). Flexibility and cost are important robot selection criteria for an SME. Naturally, high cost and inflexibility become barriers to the purchase decision (Bi et al, 2015). Manufacturing environment, product design, production system and cost involved are some of the most influencing factors that directly affect the robot selection decision (Chatterjee et al, 2010).

Within the Technological Context, “selection of a robot for a specific industrial application is one of the most challenging problems in the real time manufacturing environment. It has become more and more complicated due to an increase in complexity, advanced features and facilities that are continuously being incorporated into the robots by different manufacturers”[42] (Chatterjee et al, 2010). Robots have not been successfully implemented within product finishing due to reasons such as lack of accuracy and repeatability. For example, “geometrical diversity is a considerable challenge when traditionally manual manufacturing processes such as hand-grinding and polishing need to be automated”[43] (Cavada and Fadon, 2013). There can

[40] Braun, T; Hausel, F; Bauer, J; Wittler, O; Mrossko, R; Bouazza, M; Becker, KF; Oester-mann, U; Koch, M; Bader, V; Minge, C; Aschenbrenner, R; Reichl, H. 2008. Nano-particle enhanced encapsulants for improved humidity resistance. 58TH ELECTRONIC COMPONENTS & TECHNOLOGY CONFERENCE, PROCEEDINGS, 2008, page 198 [6]

[41] Chioreanu, A; Brad, S; Brad, E. 2013. Knowledge Modelling of E-maintenance in Industrial Robotics. INTERDISCIPLINARY RESEARCH IN ENGINEERING: STEPS TOWARDS BREAKTHROUGH INNOVATION FOR SUSTAINABLE DEVELOPMENT, FEB 25–MAR 01, 2013, page 603 [12]

[42] Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, OCT, page 483 [10]

[43] Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, page 275 [8]

be additional challenges in advanced machinery. "An industrial part may need to be partitioned into multiple patches because of its complexity. The trajectories of all patches must then be connected in order to minimize the material waste and process cycle time"[44] (Chen and Xi, 2012).

A barrier to the adoption of micro- and nano-manufacturing technologies is the complexity of the high precision assembly process itself. It is challenging to build a physical model to establish the relationship between an assembly process and its process parameters (Li et al, 2014). Also, there are formidable challenges in the conception and design of whole products and systems. It is challenging to side-step packaging and interconnect to integrating micro-capabilities directly into macro products. This means leaving behind component-level hierarchical design and manufacture and adopting a holistic approach to both (Topham and Harrison, 2008). Finally, there is a need to better detect size and type defects, improve the reliability of inspection and probability of detection (Bond, 2015). However, recent progress in the design of photonic devices and complete on-chip electro-optic systems and interfaces promises tight and large-scale monolithic integration of silicon photonics with microelectronics. This enables natural scale-up to manufacturing and rapid advances in device design due to process repeatability – both being drivers for the adoption of micro and nano manufacturing technologies (Popovic et al, 2015).

There are still a great many unresolved issues that have hindered additive manufacturing's performance, thereby limiting its application to high tolerant jobs. These challenges highlight various aspects of production such as product requirements, process management, data management, intellectual property, work flow management, quality assurance, resource planning, etc. Productivity of the additive manufacturing process is still very low, especially for simple large-volume parts. Products must be made reliably and predictably. Another major known drawback in additive manufacturing is poor dimensional accuracy and poor surface finish (Mahamood et al, 2014). Hence, monitoring and closed loop control systems are needed (Everton et al, 2015). The lack of standards in additive manufacturing impedes its use for parts production, since "industries primarily depend on established standards in processes and material selection in order to ensure the consistency and quality"[45] (Mani et al, 2014).

In order to ease the implementation of additive manufacturing technologies, DARPA now addresses the systematic barriers to implementation rather than the technology itself: the Open Manufacturing programme is enabling rapid qualification of new technologies for the manu-

[44] Chen, HP; Xi, N. 2012. Automated Robot Tool Trajectory Connection for Spray Forming Process. J. Manuf. Sci. Eng.-Trans. ASME, vol. 134, APR, page 021017-1 [11]

[45] Mani, M; Lyons, KW; Gupta, SK. 2014. Sustainability Characterization for Additive Manufacturing. J. Res. Natl. Inst. Stand. Technol., vol. 119, SEP 22, page 419 [49]

facturing environment. Moreover, it is expected that developing computational, communicational and control approaches of additive manufacturing will help validate and move it to the factory floor (Cooper, 2014). Also within the Environmental Context, systems as Minimum Quantity Lubrication (MQL) or Cooling (MQC) have been emerging in advanced machinery over the years in order to reduce pollutant emissions and to solve problems related to workers' health (Priarone et al, 2015).

Within the Organizational Context, the emergence of the cloud computing paradigm can be a driver of new high performance manufacturing systems. Cloud computing can be utilized as a hosting platform for autonomous data mining and cognitive learning algorithms. This brings "new service models and research opportunities to the manufacturing and service industries with advantages in ubiquitous accessibility, convenient scalability and mobility"[46] (Yang et al, 2015).

Within the Technological Context, new fabrication techniques in additive manufacturing provide the necessary tools to support the need for increased flexibility and enable economic low volume production, cutting costs due to a significant reduction in material waste (Mellor et al, 2014). One driver of additive manufacturing can be the way it gives designers the opportunity to create their products in ways which were previously considered impossible to manufacture, such as customization and new design possibilities (Singh and Sewell, 2012). Indeed, part consolidation by additive manufacturing could bring great benefits in future product design applications (Jansen et al, 2014).

Robot manufacturers are looking for ways to actively engage human operators in a constructive fashion. Indeed, "the integration of human operators into robot-based manufacturing systems may increase productivity by combining the abilities of machines with those of humans"[47] (Ding et al, 2011). For example, more intuitive ways are developing to programme robots (Neto, 2013).

Table 4. Barriers and drivers in high performance manufacturing

	Barriers	Drivers
Environmental Context	• The additive manufacturing challenges relate to environment and energy, to scale and cost of production, and structural performance • Difficulty in developing a cost effective	• Funders focus on the systematic barriers to implementation rather than the technology itself • Developing cyber-enabled manufacturing systems, that is computation, communi-

[46] Yang, SH; Bagheri, B; Kao, HA; Lee, J. 2015. A Unified Framework and Platform for De-signing of Cloud-Based Machine Health Monitoring and Manufacturing Systems. J. Ma-nuf. Sci. Eng.-Trans. ASME, vol. 137, AUG, page 040914-1 [83]

[47] Ding, H; Wijaya, K; Reissig, G; Stursberg, O. 2011. Optimizing Motion of Robotic Mani-pulators in Interaction with Human Operators. INTELLIGENT ROBOTICS AND APPLICATIONS, PT I: ICIRA 2011, DEC 06–08, 2011, page 520 [34]

	solution to additive manufacturing of non-metals and metals • Difficulty in estimating the required precision, without unnecessarily high accuracy of the equipment used and, therefore, without inflated costs • Nano manufacturing generally lacking basic processes common to manufacturing-qualification	cation and control approaches will help in validating additive manufacturing and moving it to the factory floor • Adapted digital workflow promises advantages in the introduction of process documentation, aspects of quality control, cost minimization and in the efficiency improvement • Promises in reduction of pollutant emissions and the problems related to workers' health
Organizational Context	• Managerial action needed with regard to advanced planning procedures, user involvement plans, communication channels, company labour policies and continuous training programmes • Lack of expert knowledge • Challenges in the conception and design of whole products and systems • Difficulty in managing information flow and system complexity of production cells that incorporate equipment from different producers	• Cloud computing paradigm can be utilized as a hosting platform for autonomous data mining and cognitive learning algorithms; these bring new service models in the manufacturing and service industries with advantages in ubiquitous accessibility, convenient scalability and mobility
Technological Context	• The selection of a robot for a specific industrial application is challenging • Robots do not adapt well to dynamic environments, do not offer rich human-robot interaction and are not simple for end-users to programme • The integration of micro-components into macro-scale products is non-trivial, conventionally posing difficult questions and compromises in the domains of packaging, interconnection and design • Difficulty in detecting, sizing and typing defects, need to improve the reliability of inspection and probability of detection • Complexity of the high precision assembly process • Productivity of additive manufacturing process is still very low: must make products reliably and predictably, monitoring and closed loop control are needed • The lack of standards in additive manufacturing impedes its use for parts production; must ensure the consistency and quality	• In microelectronics, smaller feature sizes lead to higher frequency operation and lower power consumption • Promises of platforms tailored to a vast array of emerging applications, which provides versatility, low costs, installation and operational flexibility, safety and reliable operation characteristics • New materials can add new functionalities: a great potential of different nanoparticles as additives for enhanced product performance • Promises of opportunities to create products in ways which were previously considered impossible • The integration of human operators into robot based manufacturing systems may increase productivity by combining the abilities of machines with those of humans • More intuitive ways are developing by which to programme robots

3.3 Barriers to, and drivers of, sustainable manufacturing technologies

3.3.1 Financial and General Management Perspective

A general barrier to the adoption of sustainable manufacturing technologies is the fact that management needs to balance business profit with environmental impacts and benefits and is challenged by a low realisation of market benefits (Granly and Webo, 2014). Technical opportunities need to be converted into concrete benefits with quantifiable impact. For example, nanomaterial fabrication delivers substantial tailorability beyond a traditional material data sheet. However, tailorability must be integrated into agile manufacturing and design methods so as to further optimize the performance, cost and durability (Vaia, 2012). Another barrier, in nano scale manufacturing, is a need to define nano-protective environmental health and safety practices (Engeman et al, 2013).

Within the Organizational Context, converting engineering nanotechnology reliably into useful applications and products requires knowledge about manufacturing at the nanoscale, integration of nanoscale materials and devices with more conventional technology and predictive modelling (Romig, 2004). More generally, barriers to sustainable manufacturing technologies relate to employee buy-in, competence and time. For example, enterprises have difficulties in allocating resources to initiatives that are not viewed as being directly related to their core function of manufacturing the product or providing the service (Cote et al, 2008).

Within the Technological Context, the application of state-of-the-art process systems engineering technologies is limited for small scale processes. The limitation is particularly high when attempting to optimise process operation (Dunnebier, 2008).

Within the Environmental Context, if general standards and communication aspects are in, customer's awareness is much more likely to follow than in cases where information about technologies is hidden (Ruhnau and Bunzel, 2014). Moreover, scale and supply-chain development do affect the adoption of sustainable technologies. For example, the role of innovation, the importance of manufacturing scale, and the opportunity for global collaboration leads to an increase in the installed photovoltaics capacity (Goodrich et al, 2013). Local authorities can also play an important role in driving sustainable manufacturing technologies. For example, local authorities can develop Sustainable Product Service Systems enabling policies as well as supporting novel networks of stakeholders (Vezzoli et al, 2015).

One driver for the formulation of new, more sustainable managerial practices combining energy efficiency and product innovation are efficiency considerations, market attention, and greening of innovation. They make company management consider more carefully the specificities and interactions of different types of products and process innovations and their environmental implications (Gerstlberger et al, 2014).

3.3.2 Customer Perspective

When considering new customer offerings, the unique advantage of nanotechnology is due to nanoscale physical and chemical properties that are quite different from those encountered in microscopic or macroscopic materials and devices. For example, integrating advanced nanotechnology with biotechnology helps to improve enzyme activity, stability, capability and engineering performances in bioprocessing applications (Misson et al, 2015). Fibres and fibre reinforced polymer composite products offer many significant benefits such as light-weight, superior mechanical properties, extended service life, low maintenance and resistance to corrosion (Kalla et al, 2012). They also provide positive environmental benefits with respect to ultimate disposability and raw material use (Postek et al, 2008). Fibres such as ones made from seed (coir) and animals (chicken feather) improve sustainability as they are secondary or made from waste products (Ramamoorthy et al, 2015).

3.3.3 Operations Perspective

Within the Environmental Context, the ethical and social consequences of nanotechnologies encompass many key areas associated with development, such as privacy, security, the environment, food and agriculture (Khan, 2014). The potential adverse human health effects of manufactured nanomaterial exposure are not yet fully understood, and human exposures are mostly uncharted (Engeman et al, 2013). The basic processes common to manufacturing are not generally in place for nanotechnology-based products: qualification of raw materials, continuous synthesis methods, process monitoring and control, in-line and off-line characterization of product for quality control purposes and validation by standard reference materials (Postek et al, 2008). For example, nanoparticle's manufacturing technology challenges include operations ranging from particle formation, coating, dispersion, to characterization, modelling and simulation (Zhao et al, 2003).

Within the Organizational Context, sustainable manufacturing technologies require a combination of multiple expertises. For example, manufacturing of biocomposites from renewable sources is a challenging task involving metals, polymers and ceramics (Namvar et al, 2014).

Within the Technological Context, one barrier to the adoption of sustainable manufacturing technologies is the challenges in cost-benefit analysis. Firms' metrics typically fall into product-level metrics across the life cycle and facility-level metrics. Neither is sufficient for firm-wide cost-benefit analyses of modifications that affect multiple products and value-chain stages. Moreover, modifications to product design, material procurement, manufacturing, energy/water use, distribution, use, and disposal often create trade-offs, improving some aspects while worsening others (Meinrenken et al, 2014).

In biomanufacturing, scaling of operations can be a challenge. Biocomposites are explored at lab scales but they have not yet found large-scale commercial applications (Namvar et al, 2014). For example, the current 3D bioprinting technologies need to be improved with respect to the mechanical strength and integrity of the manufactured constructs (Zhang and Zhang, 2015). New biomaterials have uncertainty in physical properties, such as viscosity and surface tension coefficient. Therefore, the 3D printing process requires a large number of trials in order to achieve proper printing parameters (Ren et al, 2014). There is a lack of effective design software for 3D printing and prototyping also (Yoo, 2014).

Within the Organizational Context, a firm's proficiency in leveraging IT technical infrastructure flexibility, IT personnel skills and IT-business alignment enables the integration of IT in the environmental management processes to improve environmental performance (Wang et al, 2015). Moreover, current IT systems can support the collection of all the information needed using computer-aided design (CAD), enterprise resource planning (ERP), and product life-cycle management (PLM) systems. For example, suppliers can provide component information to enable the manufacturer's design for disassembly and recycling analysis (Kuo, 2010). Similarly, current IT systems make it possible to establish system of key performance indicators (KPIs) that evaluate sustainability of the company's products across its brands and operating countries, and can be determined at any level (single product, brands, or regions) (Meinrenken et al, 2014).

Within the Technological Context, advantages of advanced manufacturing techniques include design flexibility, reduced processing costs, reduced waste, and the opportunity to more easily manufacture complex or custom-shaped structures (Sidambe, 2014). For example, the adoption of additive manufacturing technology can be used to reach transparency in terms of energy and financial inputs to manufacturing operations (Baumers et al, 2013). Similarly, an improved power monitoring allows for the quantification of energy efficiency, thus enabling control of peak power use and cntrol of the process stability (Humphrey et al, 2014).

Table 5. Barriers and drivers in sustainable manufacturing technologies

	Barriers	Drivers
Environmental Context	• The potential adverse human health effects of manufactured nanomaterial exposure are not yet fully understood, and exposures in humans are mostly uncharted • Need to identify the needs of manufactured nanomaterial companies in developing nano-protective environmental health and safety practices • Management need to balance business profit with environmental impacts and benefits, and is challenged by a low realisation of market benefits: difficult to convert technical opportunities into concrete benefits with a quantifiable impact • Life cycle assessment methodologies not mature enough to be applied at the scale of entire product portfolios: neither product-level metrics nor facility-level metrics are sufficient for firm-wide cost-benefit analyses that affect multiple products and value-chain stages	• The role of innovation, importance of manufacturing scale and supply-chain development do affect the adoption of sustainable technologies • Local authorities can play an important role in developing sustainability enhancing policies as well as supporting novel networks of stakeholders • New materials are emerging from secondary sources or from waste products; provide positive environmental benefits with respect to the ultimate disposability and raw material use • The Internet of Things paradigm promises to increase the visibility and awareness of energy consumption and financial inputs to manufacturing operations
Organizational Context	• General challenges with respect to employing sustainable manufacturing technologies relate to employee buy-in, competence and time • Difficulty in combining multiple expertise the sustainable manufacturing technologies typically require • Challenging to manage variety throughout the entire products life cycle; firms have to balance the dual goals of reducing variation and promoting variation in their product configuration activities	• Efficiency considerations, market attention, and greening of innovation make company management to consider more carefully the specificities and interactions of different types of products and process innovations and their environmental implications • Current IT systems can support the collection of all the information needed to enable the manufacturer's design for disassembly and recycling analysis
Technological Context	• Difficulty in gaining all the information necessary to plan for the recycling evaluation; modifications often create trade-offs, improving some aspects while worsening others • Life cycle assessment methodologies are currently not mature enough to be applied at the scale of entire product portfolios • Continuous, process-like manufacturing places special requirements to the Six Sigma toolbox e.g. with respect to advanced control, dynamic simulation and dynamic optimisation • Difficulty in scaling up of bioprinting operations; challenges with respect to the mechanical strength and integrity in the manufactured constructs, lack of an effective design software	• Continuous manufacturing promises sustained operation with consistent product quality, reduced equipment size, high-volumetric productivity, streamlined process flow, low-process cycle times and reduced capital and operating cost • Improved power monitoring allows for the quantification of energy efficiency, the limiting of expensive peak power use and the control of process stability • The unique advantage of nanotechnology is due to nanoscale physical and chemical properties that are quite different from those encountered in microscopic or macroscopic materials and devices

4 Case study analysis

From the literature study, we acquire a broad view of AMT and of the drivers and barriers affecting investment in these technologies in general. To understand the specific situation in Europe, we have carried out initial case studies in seven European companies. In the next phase, eight new cases will be added. The literature study is based on an analysis of thousands of articles, mainly from academic research. As a consequence, the focus in this study is in the main on emerging technologies. In the case study, the focus is more on advanced technologies on the market. While there is a great deal of discussion about maturity of technology in the literature study in Annex I, in the case study the focus is on factors affecting the ability of the companies to invest and implement existing but new technologies.

In the case study, we use a semi-structured interview approach in order to broaden our understanding of AMT and its drivers and barriers to investment. Through open questions, we strive to identify drivers and barriers that have not been identified earlier, and to learn more about underlying factors than in previous studies.

In the case study interviews, we first asked the interviewees to define what they thought were the most important drivers and barriers to investment in AMT, and secondly we cross-checked these answers with more detailed discussions on investment decisions already held in the companies.

In this chapter, we describe the setup of the case study and then go on to present the preliminary results of the first seven cases.

4.1 Case study design

The main steps of our case study approach are:

- Set up case study template based on literature study;
- Choose case studies in each region;
- Carry out case study interviews;
- Complete the case study documentation for analysis.

For each interview, we reserved two to three hours in the company. The interviews were and will be carried out mainly in the companies by two researchers from the research organisation responsible for the interviews in the area. Each interview is documented based on the interview template in order to enable analysis and comparison of cases. The main questions in the interviews focus on the different categories barriers and drivers, accompanied by general questions, see also Figure 4 below (see also Annex II Interview questionnaire).

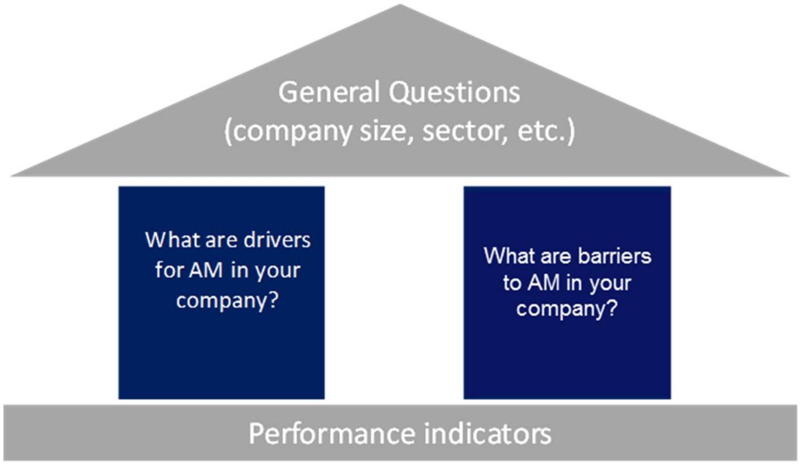


Figure 4. Main pillars of the semi-structured interview guidelines

The main steps of the analysis are:

- Identification of barriers, drivers and readiness factors in each case
- Comparison of cases in one region to identify differences between companies in different positions in the value chain
- Comparison of cases to identify potential differences between industries and regions

The interviews are carried out and documented in English. The initial analysis of barriers, drivers and readiness factors in each company will be carried out by the responsible organisation and will be documented case by case in English. This information is used for a further analysis in regions, between regions and between industries.

4.2 Choice of cases

The aim of the case studies is to identify and analyse the internal and external drivers that have enabled companies to invest in advanced manufacturing technology, and what barriers have slowed down further diffusion of the technology. The choice of leading adopters of advanced technology gives us a good understanding of drivers, but it gives us less information on barriers. Yet, a good understanding of the causality behind drivers will also give an understanding of what can slow down diffusion of new technology, and what can become barriers if not properly addressed. Since there has to be a homogenous coverage of the different regions of Europe, with a clear focus on SMEs, the distribution of the case studies among partners and regions is planned as shown in Table 6. For each region, two SMEs and one large company is chosen for case study interview.

Table 6. Distribution of the Case Studies

	Central Europe (ISI, IDEA)	Northern Europe (VTT)	Southern Europe (ITIA)	Western Europe (ISI, IDEA)	Eastern Europe (ISI)	Sum
SME (<250 employees)	2	2	2	2	2	Approx. 10
Large compa-nies (>2000)	1	1	1	1	1	Approx. 5

To obtain a geographical spread of the case studies, we divide EU into five geographical regions (Northern, Southern, Western, Eastern and Central Europe, see Table 5). By choosing lead companies in main industry sectors in each region, we identify drivers affecting existing investments. The central objective is to identify leading SMEs in each region. If possible, we will also strive to find cases from different positions in the value chains: OEM (large/SME), component manufacturer (large/SME) and subcontractor (SME). Similarly, there is a need to take a closer look at the different challenges of manufacturers of discrete goods on the one hand and process manufacturers on the other hand — both manufacturing types need to be covered by the case study. To sum up, criteria for choosing a company for our set of case studies are:

- Region of the company (to cover all parts of Europe);
- Size of the company (clear focus on SME, supplemented by large companies);
- Position in the value chain (to cover different positions);
- Process manufacturers or manufacturers of discrete goods (to gain an insight into the challenges of both spheres).

In order to gain a deep insight into the idiosyncrasies of companies and the challenges they have to deal with when adopting (or not adopting) AMT, it is of great importance not only to find the right companies but also to find the right expert to talk to within a company. For our project, it is of the utmost importance to interview either the owner of the company (especially for SMEs) or the head of production or the CEO (especially for large companies). Companies will be contacted by members of each regional partner relying on their direct contacts to companies and also on their network of intermediates such as clusters and industry related associations, see also Table 6 below.

Responsible organisations for case studies in each geographical region are:

- Central Europe (DE, AT, PL, CZ, SK, HU) / (ISI, IDEA)
- Western Europe (FR, BE, NL, LU, UK, IE) / (ISI, IDEA)
- Northern Europe (DK, SE, FI, LV, LT, EE) / (VTT)
- Southern Europe (ES, PT, IT, GR, MT, CY) / (ITIA)

- Eastern Europe (RO, BG, SI, HR, Serbia) / (ISI)

A list of case companies has been compiled and provided to the EC and EASME, but for confidentiality reasons, it is not published.

4.3 Results of initial case interviews

4.3.1 Description of case company

In the first phase of the ManStu case study, we have carried out interviews in seven companies. In this report, we present the results from the analysis of these interviews. A comprehensive analysis of all fifteen cases will be covered in a later deliverable in the ManStu project.

Of the analysed companies, five are SMEs and two are large companies. Five companies are both users and suppliers of AMT and two companies are AMT users. In this set of companies two are from Eastern Europe, four from Southern Europe and one from Northern Europe.

The two AMT user companies are large or mid-cap internationally operating companies producing consumer goods. Financially, these companies are on a positive path, but are not yet very strong. However, these two companies have the most experience of various AMT among the interviewed companies. One of the AMT user companies reports that it started investing again in 2014 after a negative period in 2011–2012.

The two AMT user companies both mention several types of high performance manufacturing technologies, such as robots, material handling systems, automated warehouse systems and additive manufacturing. One of them has also been active in the area of ICT-enabled technology. Supply chain management and enterprise resource management systems are up and running, and the company has also made tests with Virtual Reality simulation technology.

The AMT supplier companies in this group are SMEs. Three of the companies in this group are producing large highly automated production machinery. One produces high quality production equipment and one high quality production tools. Four out of five companies in this group are growing, and all of them have a stable financial situation. However, although their own products are technically advanced, there are clear differences in how they apply AMT in their own production. Four of these companies have invested only sparingly in high performance manufacturing technologies. The fifth AMT supplier has invested in automatic production equipment to improve the efficiency of both its R&D process and its manufacturing process.

Three of the AMT suppliers mention investment in ICT-enabled intelligent manufacturing technology. This technology is used in product development and in production, but is also as a central part of the product. In service business ICT-enabled intelligent manufacturing technology is part both of the physical product and of the customer service.

Sustainable manufacturing technology is mentioned by four AMT suppliers.

Four AMT suppliers report that the financial situation has allowed for continuous investment and growth during the last years. One of these reports having invested in machinery and equipment at a level of five per cent of turnover per year. One company made its major investments before 2009, and one report mainly investment in own R&D during the last years.

The seven case companies are described briefly below. For interviewee and company confidentiality reasons, the companies are here presented anonymously.

> *North 1* is a family-owned SME from Finland. The company focuses on design and manufacture of highly customized automated manufacturing systems for heavy manufacturing industry. The company personnel are highly skilled, with roughly half of the personnel having a degree in engineering. About 90 % of the production is exported, about 60 % outside Europe. Major investments in production plant and product development were made in 2003 and 2004 with an enlargement in 2009.
>
> *East 1* is a Hungarian SME designing and manufacturing customized measuring equipment for industry. This is a privately owned limited company with solid finances. It grew rapidly between years 2008 and 2014, having invested heavily in production facilities and product development in 2006 and 2007 respectively. In 2013–2014 the company invested in an enlargement of its plant facilities.
>
> *East 2* is a Serbian SME specialized in development and production of welding equipment and tools for industry. In addition to the R&D and production, the company performs, repairs and maintains all types of welding units, and offers training for professional users. The company employs mechanical, electronic and IT engineers for development of customer specialized technology. The company has a huge co-operation network which enables it to develop and produce customer-specialized systems of highly automated mechanic and electronic parts for the welding and cutting tools.
>
> *South 1* is a mid-cap company from Spain. It develops, produces and supplies household furniture in the Iberian Peninsula. The company has a strong focus on technologies and services. It strives to improve its competitive position by technological innovation and design, by the quality of its products and through its customer service.
>
> *South 2* is a family-owned machine tool company from Spain specializing in building and selling high added value machining centres all over the world. It is an SME and its competitiveness is based on high quality products, flexibility and customization. The company is constantly improving its designs, product range and services related to the machine. This is how it can offer exactly what the customers need and not just a ”standard” machine.

South 3 is a social economy company offering precision cutting tool and solutions for various industrial uses and for the building sector. Its tool design and advanced geometry ensures the best finishing and performance in all materials designed. The use of modern coating allows an increase in the cutting speed. The company export more than 80 % of its production.

South 4 is the only large company in the group of companies interviewed. It is one of the major household appliance manufacturers in the world, with approximately $20 billion in annual sales, and manufacturing and technology research units in about 70 countries. In a mature and concentrating market, led by a few big competitive players, the company leverages a broad global scale, relying on regional divisions to meet local consumer's preferences. With two recent acquisitions, the company has become more geographically diverse and realized market share growth. Its main competitive advantages are based on high economies of scale, reduction in labour costs, in particular in assembly operations which are relevant for an OEM, and on automation.

The cases, their AMT investments and arguments for investing or not investing are described in more detail in Table 7.

Table 7. Case company descriptions

Company code	Basic data	Region/ country	User/ producer	AMT investments	Drivers/barriers
North 1	- SME - Family owned, - Fast growth 2000–2009 - Financially doing well - Main investments made 2003–2004, 2009	North/ Finland	User Producer	Sustainable manufacturing technology: factory facilities and sustainable technology (2003, 2009)	+ The company invested heavily in sustainability in order to *improve competitive edge*. Being able to show the customer that the company is capable of operating very sustainably can convince the customer of their ability to provide high quality, sustainable products. Productivity and quality of performance comes first, but after this sustainability is also important for the customer. + Sustainability is an *image issue* for the customers + The factory is a very *good working environment* for the personnel.
				ICT enable manufacturing technology: product development (2004, continuously)	+ Flexible automation *improves productivity* in heavy manufacturing industry. + The capacity of the computers has grown, enabling the development of *the flexibility of automation systems*
				High performance manufacturing technologies (not invested)	- The manual assembly process on one-off products is not suitable for automation. Part production is outsourced to suppliers.
East 1	- SME - Family owned - Fast growth 2008–2014 - Solid financing - Main investments 2006–2007, enlarge-	East/ Hungary	User Producer	High performance manufacturing technologies: automation of PCB development and manufacturing	+ higher efficiency of our R&D processes + development of electronic boards by using computers, + development of the products without pilot/model development + simulation of complex functions, + testing and simultaneously improving the quality without any additional investments + achieving high performance improvements in manufacturing of our electronic products: + automated manufacturing of PCBs + programmable manufacturing processes + automated quality control

	ment 2013–2014				+ We offer a much *better quality of products* for a lower price on the market + We are much *more flexible* than before + *Higher quality / lower price* + More efficient manufacturing processes – *less waste and scrap*
				ICT-enable technology: intelligent calibration lab	+ Exploiting the lab *improves* our *financial situation* – our better financial situation is one of the reasons why we invest in this equipment + We are able to *develop, produce and to calibrate our products* – this is why our customers want to work with us + This is our USP + Our lab is our *best school* + *Higher quality* requirements + All meters *have to be* calibrated and *certificated*
				ICT-enabled technology: simulation of development and manufacturing processes	+ *Flexibility* and *speed* of R&D and of manufacturing + Only some exceptions + More efficient manufacturing processes – *less waste and scrap*
				ICT-enabled technology: GPRS and Bluetooth communication technologies	+ Without this technology we would *lose our customers* + *All suppliers* on the market *offer* this technology + *Market requires* such data transfer technologies
				Sustainable manufacturing technology: long-life meter devices	+ Because of the high demand for digital meters with low energy consumption (long-life meters) we invest in the development of new products
				High performance manufacturing technologies: additive manufacturing technologies – 3D printers (not invested)	- Too expensive - There is no subvention in Hungary or in the EU
East 2	- SME - Family owned	East/ Serbia	User Producer	High performance manufacturing technologies: development of welding	+ The R&D is a part of a project. We share the development costs with the customers + We are only 2–3 kilometres away. + We offer our customers a continuous availability for maintenance and training for

	- Solid finances - Growing - Investing 5–10 % in R&D yearly			and cutting tools which are compatible with well-known robot brands	operators + We offer a good quality at a fair price + Our engineers are ready to learn and to adopt their competences to new challenges. This allows us a high flexibility, not only in R&D but also in manufacturing + Our automated welding tools improve the process performance of our customers. Clearly, this is the main reason why they invest in this technology + Our customers want to have a good supplier who is always there if they have a problem
				ICT-enabled technology: GSM communication technology – communication between the developer and the automated tool	+ With this technology we are able to ensure the function of our manufacturing tools without long disturbances. Thus, this boosts the competitiveness of our products and our services + With this communication technology we are learning about the behaviour of our products in practical use + Improvements of maintenance + The customer wants to have a production with minimum disturbances. This technology ensures a better control of our tools
				High performance manufacturing technologies: automation of manufacturing processes (not invested)	- This technology is too expensive – the effects of this technology on the performance of the single unit manufacturing are not significant - Each project is a new challenge for our engineers. They develop the tool, test it and install it in the manufacturing process of the customer. These processes cannot be automated - The company produces highly specialized products – it is not mass production
South 1	- Large (Mid cap) company - Financial break even	South/ Spain	User	Investing in AMT (general)	- The excessive concentration of sales in a few large customers introduces an element of risk in increasing productive capacity. Any loss of a single customer can *compromise the return on investment*. - *High bureaucracy* of applications for European grants for R&D and innovation and low success rates
				High performance manufacturing: Industrial robots	+ Improve products quality + Reduce Labour cost + Reduce lead time

				High performance manufacturing: Handling systems	+ Improve safety of employees + Reduce labour cost + Reduce lead time
				High performance manufacturing: Automated Warehouse Management	+ Improve safety of employees + Reduce labour cost + Reduce delivery time + Avoid mistakes in goods identification
				High performance manufacturing: ICTs applied to machinery / production control through computers, and mobiles devices -smart phones	+ Provides a complete remote control of the factory flow and machineries to the production and maintenance managers.
				Sustainable manufacturing technology: Control system for shut down of machines	-
South 2	- SME - Family owned - Good financial situation - Growing	South/ Spain	User Producer	High performance manufacturing: Factory facilities	+ This is going to enable growth for several years. As part of this investment, the production facilities were planned for a very high standard of technology to be demonstrated to customers and to be effective and flexible in their own production
				High performance manufacturing: production automation (not invested)	- Although the company is a producer of highly automated production equipment, it has made only limited investment in automation in its own production. - The main reasons for this are the type of production it has, and how the production is organized in the value chain. - First, the products are customized (one-off) products with limited opportunity for repetition or economies of scale. - In the production, the company focuses on assembly, and the part production is to a large extent outsourced to a highly devoted supplier network. - The assembly work is to a large extent manual.
South 3	- SME - Good	South/ Spain	User	Sustainable manufacturing technology: Sustainable	+ *Increase capacity* (4) + *Safety* is the first issue (5)

	financial situation - Growing		Producer	manufacturing technology and logistics	+ Very important in our company because of our culture (3) + Need to be updated and keep *competitive* (5)
South 4	- Large company - Listed company - Growing turnover - Company return growing since 2013	South/ Italy	User	High performance manu-facturing: Industrial robots/ handling systems	+ *Adopted and running in practice*
				High performance manu-facturing: Automated Warehouse Management Systems	+ *Adopted and running in practice*
				High performance manu-facturing: Additive manu-facturing	+ *Adopted and running in practice.* + *This technology is used at the moment only in a prototyping phase. The company is very interest in exploring its advantages also in the production phase*
				ICT-enabled technology: VR / simulation in product design	+ *Made some tests* - The company carried out a project for the introduction of these technologies but results were not exciting in terms of experienced advantages. Consequently, these technologies are not adopted in practice. - There are multiple reasons. The first one is of a cultural type. The company has a deep lean manufacturing culture and tradition. Lean manufacturing is in favour of people involvement, and this is also done by using a wide set of manage-ment/organizations instruments which are supported by paper documents as a car-rier enabling information sharing and intra-organizational dialogue. Thus, digital tools are not immediately suited to lean manufacturing practices, at least in the conception of company culture. - The second reason is that the background of the company derives from "times and methods" practices. Thus, people do not have competences able to appreciate and use digital tools. - Finally, some experiences were gained recently with simulation, but they did not result in a positive result.

				ICT-enabled technology: Supply chain management with suppliers/customers	+ *Adopted and running in practice* + *Interesting experiences with electronic Kanban with suppliers.* - The current system needs additional work for updating information. One of the main experienced barriers is the cultural readiness of people (both of the company and of suppliers' companies) to understand and change their operation processes accordingly
				ICT-enabled technology: Enterprise resource planning	+ *Adopted in practice*
				Sustainable manufacturing technology: Dry processing/minimum lubrication	+ *Adopted*
				Sustainable manufacturing technology: Combined cold, heat and power (Bi-/Trigeneration)	+ *The company established a partnership with its energy provider for the installation of a co-generation system in order to minimise heating costs of manufacturing/assembly processes. Through this solution the company is also able to sell energy in the network.*
				High performance manufacturing: Technologies for safe human-machine cooperation (not adopted)	- The company is currently exploring the viability and advantages of such technologies. There are ongoing projects on man- machine cooperation for assembly operations.
				High performance manufacturing: Processing alloy construction materials (not adopted)	- Not applicable to the present process.
				High performance manufacturing: Processing composite materials (not adopted)	- At the moment, the company is not using composite materials in its products
				High performance manu-	- Very few micro-mechanical components are used. When employed, components

				facturing: Manufacturing micromechanical components (not adopted)	are bought from external suppliers
				ICT-enabled technology: VR / simulation in production reconfiguration (not adopted)	- There are multiple reasons. The first one is of the cultural type. The company has a deep lean manufacturing culture and tradition. Lean manufacturing is in favour of people involvement, and this is also done by using a wide set of management/organizations instruments which are supported by paper documents as a carrier enabling information sharing and intra-organizational dialogue. Thus, digital tools are not immediately suited to lean manufacturing practices, at least in the conception of company culture. - The second reason is that the background of the company derives from "times and methods" practices. Thus, people do not have competences able to appreciate and use digital tools. - Finally, some experiences were made recently with simulation, but they did not result in an enthusiastic result.
				ICT-enabled technology: Product Lifecycle Management Systems (not adopted)	- A significant attempt to adopt this technology was made in the past, but with negative results. The barrier was mainly of organizational type. In fact, while product development is carried out centrally at corporate level, logistics and manufacturing operations are at local level. By definition, PLM should integrate all information from design to end of life. However, company organization makes the integration of such information difficult since product development and manufacturing/logistics are supported by separated systems that do not communicate. The only linkage between the systems is the BOM. Investments needed in order to integrate the two systems and the organizational distance in terms of systems and priorities between the various functions and units makes very complex to agree on them.
				Sustainable manufacturing technology: Recuperation of kinetic and process energy (not adopted)	- The process is not very energy consuming, except for furnaces. Thermal insulation was adopted for this.
				Recycling and waste/disposal manage-	- Waste and end of life products are recycled by external operators. Only plastic process scraps are re-melted in production. There are difficulties in employing recy-

				ment technologies (not adopted)	cled materials in new products since regulatory constraints do not allow the use of contaminated materials for the production of parts that will have to interact with food. - End of life take back options that could enable remanufacturing practices or the extraction of spare parts are at the moment excluded due to the prohibitive logistics costs and also due to the low value of cores.
				Sustainable manufacturing technology: Sustainable nanotechnology (not adopted)	- Nanotechnologies are employed only for some surface finishing treatment (anti-fingerprint, anti-scratch coating).

4.3.2 Main drivers of and barriers to AMT in Europe

In part 4 of the interview questionnaire, the interviewees were asked to describe what the main drivers of and barriers to AMT investment for European companies could be, and to what extent national and European policy support or hinder investment in AMT. Based on the answers we have identified, a set of barriers emerged affecting the AMT market conditions in Europe.

1. The European AMT market is, in general, seen as very passive at the moment
2. The European AMT market is not one unified market, but there are differences between countries and regions. Some leading areas (Germany) seem to be slowing down, and others (Italy, UK, France) are showing some signs of awakening. Local or national activities and support also affect how industry in the area is investing. For instance, the Basque country has successfully supported AMT investment. There are, of course, good examples of companies which dare also to invest in other countries with high labour costs. For instance, Danish and Norwegian companies were mentioned in the interviews.
3. Some AMT user industries are facing market concentration and intensification of competition from Asia. This is true especially in the mass production of consumer goods, where the entry in the European market of Asian producers has destabilized the competition, raising dumping disputes between producers, and where relationships between competitors are strained and co-petition (cooperation between competitors) is not pursued. In the AMT market, Chinese competition has not been successful in Europe due to high quality requirements.
4. Low competitiveness of the labour force and high cost of labour is affecting the entrepreneurial climate in some European countries. This also affects how entrepreneurs and managers see investment in AMT and investment in general.
5. A central challenge is that few companies are prepared to make productivity leaps through investment in new advanced technology. Users are more willing to continue to work with already installed technology. The primary criterion for selection of a supplier is usually the price, and not the novelty of the technical solution. Especially in publicly listed companies and companies operating in low-margin markets and relying on economics of scale, management is strongly risk-adverse when considering new investments for innovation. Not only the Return On Investment is a fundamental indicator, but also the Pay Back Time. In other words, production stops, lower production rates and higher lead times due to non-robust technologies can be a real disaster. Innovation projects are launched when the return on investment is significant, and when they do not present high risks. In particular, it is very important not to invest in technologies whose advantage and robustness is not clearly proven, in order not to dam-

age the quality and reliability image of the company. Management is particularly cautious before putting in production new technologies if they have not been exhaustively tested and engineered before.

6. Lack of competence and know-how to adopt and to use new technologies is also seen as a barrier to implementation of AMT in Europe. This specifically concerns the use of complex ICT based systems with a high level of digitalization (combined electronic and software elements), especially when the implementation of the system requires input from several suppliers. In case of high performance manufacturing systems, the situation can be reverse: due to new, user-friendly technology the use is made even simpler than before.
7. In order to manage innovation risk, user companies cooperate with innovation partners which develop, customize and industrialize the technology. User companies do not have the infrastructure capable of developing and introducing technology innovations alone, but it is necessary that the innovation partners develop the technology till TRL 9. Only at this stage will users buy innovative technology and introduce it into production lines. The user companies are very careful also in the selection of these partners, since it is crucial not to bring a technological risk into production, and it is necessary that the relationship with the supplier is very strong.
8. Also the availability of reliable suppliers for the new technologies is important. Users have to rely on solid suppliers able to guarantee the supply of novel technologies to serve various production sites and the assistance in case of problems. This is a problem for SMEs whose products are not well known or are very innovative. Hence, there is a need for brokerage events.
9. Well-established companies have more references and more resources for R&D. As a consequence of this, they also get more subsidies from the EU. This affects the competition and puts SMEs in a less favourable position as suppliers of AMT. With their (limited) budgets, they are either not able to offer or they need much more time for development and production of AMT system requested by the customer.
10. Diffusion of AMT is also slowed down by complex structures in large globally operating companies. In global multinational companies, important decisions must meet the approval not only of top management in the headquarters, but also of the management of local companies and of various business units that are involved as future users of the innovation. Sometimes, it might happen that different company areas have different priorities or different understanding/intents about new technologies. To find a common agreement may result in a time-consuming process.
11. Organisational culture can also be a barrier significantly affecting investment decisions in AMT. There are multiple reasons. The first is of the cultural type. In a company with a deep lean manufacturing culture and tradition, employees at all levels are involved in development work and this is done by using a wide set of management/organizations

instruments which are supported by paper documents as a carrier enabling information sharing and intra-organizational dialogue. Thus, digital tools are not immediately suited to lean manufacturing practices, at least in the conception of company culture. Not all employees have the competences required to appreciate and use digital tools.

4.3.3 Specific drivers of and barriers to investment in case companies

In the next phase of the interviews, the interviewees were asked to identify one or a set of AMT investments that the company has already made and to describe how a set of predefined drivers affected these investments. In the same way, the interviewees were also asked to describe some AMT that the company had so far not invested in, and why they had decided not to invest. Here we first analyse in more detail how the predefined driver/barriers affected the investment or decisions not to invest in AMT.

The predefined drivers/barriers presented to the interviewees were:

- Financial situation
- Demand Situation
- Competitive Situation
- Know-how, competence and skills
- Process performance
- Customer requirements
- Legislative, regulation, political situation
- Sustainability
- Other external drivers/barriers

Below we have defined the main arguments for each driver/barrier based on the answers from the companies. The original answers are listed in Tables 8 and 9.

Financial situation:

+ The ultimate goal for any investment is, of course, to improve or at least maintain the financial situation in a changing situation, and this is what is expected from AMT as well.
- A weak financial situation and poor access to capital markets can be a barrier to AMT investment.
- Lack of public financial support for AMT investments at a national or EU level is also seen as a barrier.

Demand situation:

- + The demand situation can be improved through the customer value provided. AMT can be used to improve this value both in products and services.
- + Value to the customer is achieved through high quality products and services. ICT-enabled technology is part of the products and an enabler of services. Continuous availability for maintenance and training of operators are ICT-enabled services, which can affect how the customers invest in new technology.
- - Limited demand or uncertainty about future demand is a barrier to investment. For instance, excessive concentration of sales on a few large customers introduces an element of risk in increasing productive capacity, as the loss of a single customer can compromise the return on investment.
- - The demand for products produced using AMT is not strong enough to guarantee the return on investment in the user organisation

Competitive situation:

- + Through the use of AMT, companies can achieve unique product and service characteristics differentiating them from competition. In some cases, the AMT can provide a unique selling proposition for the company.
- + The use of AMT can also allow for more competitive pricing of products and services. In some cases, AMT can provide both better product or services quality, and a lower price than the competition.
- + Introduction of AMT can also be a necessity in order to keep up with the competition.
- + The use of AMT-like sustainable technology can improve the image of the company. Being able to show customers that you are able to operate sustainably can convince the customer of your ability to provide high quality, sustainable products and services.

Know-how, competence and skills:

- + AMT can provide data about production, products or services. This is a good opportunity for the technology provider and users to learn and to develop knowledge and competencies.
- - Use of new technologies such as Additive Manufacturing requires completely new knowledge of how to design and produce a product or service. Especially in small companies, the time and money needed for this investment can be hard to find.
- - In large companies, the complex organizational situation, with decentralized units in charge of various products, can become a barrier to the adoption of new technologies. The complexity of the organisation affects internal communication and decision making.

- Organisational culture and know-how in the company and in the value network does not support implementing high tech digital tools. For instance, lean manufacturing involving factory personnel in development can be a barrier to implementation of digital tools.

Process performance:

+ AMT can provide increased capacity compared with traditional means
+ Flexible automation can provide reductions in labour costs and improvement in labour productivity in heavy manufacturing industry
+ Cost reductions and improved productivity are central sales arguments for AMT
+ AMT improve the flexibility of both manufacturing and R&D
+ The growing capacity of computers enables the development of increasingly flexible automation systems. This is a technical enabler for AMT now and in the future.
+ AMT improve the working environment in the factory. Sustainable technology can improve the situation both inside and outside the factory.
+ AMT can improve machine usability through improvements in maintenance
- AMT are not suitable for the type of production (manual assembly, one-of-a-kind), not mature enough or too expensive in comparison with existing technology
- The technologies are too expensive or the effect on the manufacturing process is not enough to cover the extra cost of investment
- Earlier failures to implement a specific technology can become a barrier even though technology develops and the situation changes

Customer requirements:

+ In small flexible companies like the AMT provider companies interviewed, the customer requirement and fulfilment of these are at the core of their business model. AMT help these suppliers to provide solutions to these requirements through better performance of products, through better quality of products and services, and through more price flexibility.
- In mass production, user companies' increasing customer requirements are not the main drivers of the adoption of innovative manufacturing technologies.

Legislative, regulation, political situation:

+ Regulation can be a market driver creating new markets for sustainable technology. This can also be a driver for investment in AMT. For instance, high requirements on technology can make investment in AMT profitable, as it provides the
+ means to achieve these requirements.
+ Regulation can also push companies to use greener manufacturing technology

- Old regulation can be a barrier to developing and adopting AMT. For instance, re-use of components is in some areas still hindered by regulatory issues.
- There is *no* national *support for investing* in AMT.
- Applying for EU grants is *bureaucratic* and there is a low success rate for applications.
- Lack of information about new technology can in certain regions be a barrier to investment in AMT

Table 8. Drivers of investment in case companies

Positive Decision	Drivers
Financial situation	- The multinational nature of the company gives it access to capital markets. - Exploiting this technology improves our financial situation. Exploiting the lab improves our financial situation – our better financial situation is one of the reasons why we invest permanently in this equipment - If there is not a limit situation ahead.
Demand Situation	- Short geographical distance of suppliers - We offer our customers a continuous availability of maintenance and training of operators - Without this technology we would lose our customers. - We are able to develop, produce and calibrate our products – this is why our customers want to work with us
Competitive Situation	- With this technology we are able to ensure the function of our manufacturing tools without long disturbances. Thus, it influences positively the competitiveness of our products and our services - With our communication technology we are able to ensure the function of manufacturing tools developed by us without long disturbances. - The high competition level is the major reason pushing towards the adoption of process technologies that can increase efficiency and lower costs - Without these technologies we could not remain competitive on the market. All suppliers on the market offer this technology. - We offer a much better quality of products for a lower price on the market - This is our USP (unique selling proposition) - The company invested heavily on sustainability in order to improve competitive edge. Being able to show the customer that the company is capable of operating very sustainably can convince the customer of their ability to provide high quality, sustainable products. Productivity and quality of performance comes first, but after this sustainability is also important for the customer.
Know-how, competence and skills	- With this communication technology we are learning about the behaviour of our products in the practical usage

	- Competence and cultural aspects have been very important for the introduction of new technologies and lean manufacturing practices. An organizational unit was created on-purpose to purse energy and environmental efficiency. Adoption of innovations must be always motivated by economic return. - Using the lab, we develop our knowledge and competencies - Our lab is our best school
Process performance	- Improvements in maintenance - Linked to costs reduction - This technology enables us flexibility and speed of our R&D and manufacturing processes - We are much more flexible than before - This technology enables us flexibility and speed of our R&D and manufacturing processes - Increase capacity - Flexible automation improves productivity in heavy manufacturing industry.
Customer requirements	- The customer wants to have a production with minimum disturbances. This technology enables us a better control of our tools - Even if it is increasingly sophisticated in terms of quality and performance, customer demand is not the main driver in the adoption of innovative manufacturing technologies. - This technology increases the quality of our products and enables us more price flexibility - Higher quality / lower price - Higher quality requirements - Market requires such data transfer technologies - Sustainability is an image issue for the customers
Legislative, regulation, political situation	- The regulation/certificates contribute to our competition on the market - Evolving environmental regulations pushed the company to adopt new green technologies and practices. - All meters have to be calibrated and certificated before they are integrated into manufacturing systems. - All meters have to be calibrated and certificated - Safety is the first issue
Sustainability	- Sustainability is becoming a new element affecting innovation decisions in order to pursue environmental compliance and develop a sustainable image - More efficient manufacturing processes – less waste and scrap - Very important in our company because of our culture.
Other external driv-	- Need to be updated and keep competitive

ers?	- Cost reductions - The factory is a very good working environment for the personnel. - The capacity of the computers has grown enabling the development of the flexibility of automation systems

Table 9. Barriers to investment in case companies

Negative Decision	Barriers
Financial situation	- No subsidies in the country or the EU
Demand Situation	- The excessive concentration of sales in a few large customers introduces an element of risk in increasing productive capacity. Any loss of a single customer can compromise the return on investment
Competitive Situation	
Know-how, competence and skills	- The engineers should learn how to develop mechanical parts with the help of this technology – it would cost us too much time and money - Cultural barriers are important for the adoption of new tools and methods
Process performance	- When past experiences have recorded bad performances, it is difficult to reconsider the technology (simulation in manufacturing) - The manual assembly process on one-off products is not suitable for automation. Part production is outsourced to suppliers.
Customer requirements	
Legislative, regulation, political situation	- Re-use of end of life components is hindered (also, but not only) by regulatory issues
Sustainability	
Other external drivers?	- There is no information about this technology in the region - Complex organizational situation, with decentralized units in charge of various products was a barrier for the adoption of new technologies because of the difficult communications and because of the need to reach mutual agreement on investment decision. - Too much bureaucracy of applications for European grants for R&D and innovation and low success rates

4.3.4 Evaluating the importance of drivers

At the same time as the interviewees were asked to identify and describe investment decisions made, they were also asked to give a numerical value to the importance of the predefined drivers or barriers in the specific investment decision in question. On a scale from 1 to 5, number 1 was given for low importance and 5 for high importance. The scores of all the investment decisions are shown in Table 10 Importance of drivers and Table 11 Importance of barriers.

First, we take a look at the answers regarding barriers. Some of the companies describe more than one AMT investment, and all in all twelve various investments were described (see Table 10).

Table 10. Importance of drivers

Positive Decision	N1	E1:1	E1:2	E1:3	E1:4	E1:5	E2:1	E2:2	S1	S2	S3	S4	Ave-rage	Devi-ation
Financial situation	1		5				3		5	3	3	1	3,0	1,6
Demand Situation			4		5	5	5		5	4	4	2	4,3	1,0
Competitive Situation	3	3	4		4		3	5	4	5	5	5	4,1	0,9
Know how, competence and skills	1		3				3	3	5	4	3	4	3,3	1,2
Process performance	5	5		5			3	5	5	4	4	5	4,6	0,7
Customer requirements	4	5	5	3	5	5	5	5	4	3	4	1	4,1	1,2
Legislative, regulation, political situation	3		5						4	2	5	3	3,7	1,2
Sustainability	3	5		5					3	4	3	3	3,7	1,0
Other external drivers?											5		5,0	-
Average	2,9	4,5	4,3	4,3	4,7	5,0	3,7	4,5	4,4	3,6	4,0	3,0		
Devaition	1,5	1,0	0,8	1,2	0,6	0,0	1,0	1,0	0,7	0,9	0,9	1,6		

Due to the low number of cases only a rough numerical analysis has so far been made. Statistically, these results have little significance, but combined with other results from the interviews they can be used in the preparation of the online questionnaire to be made during the next stage of the ManStu project.

From Table 10 above we can see, that the respondents have answered very differently to this type of questioning. Some have answered more systematically; others have picked out the drives they consider most relevant. There is also a clear difference between how the respondents have spread their numerical answers over the scale from 1 to 5. The ways of answering indicate that a similar type of question in the online questionnaire needs to be set up in such a way as to reduce these differences.

Although the statistical significance of the answers has not been properly tested, we can make some remarks on how the interviewees have considered the importance of the various drivers. First, we can see that *customer requirements* driver has been evaluated by all respondents. It also has a rather high average value indicating that this is a driver of importance. Secondly, we see that the *process performance* driver has the highest average value with the lowest standard deviation. This can also be considered as an important driver. The average value of about four is also scored by *demand situation* and the *competitive situation*. The financial situation has clearly divided the group of respondents. Two respondents consider it not at all important, two of medium importance and two as most important. For four investments a numerical value was not given. *Know-how, competence and skills* has the second lowest average value but also a rather high deviation, indicating that this was considered important by some but not all respondents. The number of cases here is very small, but a brief observation is that the companies from Southern Europe have considered know-how, competence and skills a more important driver than the companies from other parts of Europe.

4.3.5 Evaluating the importance of barriers

The interviewees were also asked to identify one or a set of AMT that the company has not yet invested in and to describe how the predefined set of barriers affected the decision not to invest. The interviewees were asked to give a number on the scale from 1 to 5 for the importance of the barrier.

As in the case of the drivers described above, the number of cases here is also limited. All in all, eight technologies were described (see Table 11).

Table 11. Importance of barriers

Negative Decision	N1	E1:1	E2:1	E2:2	S1	S2	S3	S4	Ave-rage	Devi-ation
Financial situation		5	4	5	5	3	3	2	3,9	1,2
Demand Situation					5	2	4	1	3,0	1,8
Competitive Situation					5	3	5	1	3,5	1,9
Know how, competence and skills				4	5	3	3	4	3,8	0,8
Process performance	5		4		5	2	4	2	3,7	1,4
Customer requirements					4	3	4	1	3,0	1,4
Legislative, regulation, political situation					5	3	5	3	4,0	1,2
Sustainability					4	3	3	1	2,8	1,3
Other external drivers?			5	3			5	4	4,3	1,0
Average	5,0	5,0	4,3	4,0	4,8	2,8	4,0	2,1		
Devaition	-	-	0,6	1,0	0,5	0,5	0,9	1,3		

As in the case with the drivers in the previous chapter and also in the case of defining barriers to investment there are major differences in how the respondents have answered this question. We can, for instance, see from the average values in the various cases that there is a wide difference between how the interviewees scored these barriers. The average fluctuates between 2.1 and 5. As in the case with the drivers, this question also needs specification in the online questionnaire.

In general, we can say that the barriers have been rated as of lower importance than the drivers. Only two of the barriers have an average above four. The group *other external barriers* scored the highest. We will look into this group later. Also *legislative, regulation, political situation* scored high. Other important barriers (score about 3.5) were the *financial situation*, *know-how, competence and skills*, *process performance* and the *competitive situation.*

The *other external barriers* mentioned by the company representatives were:

- Complex organizational situation, with decentralized units in charge of various products was a barrier to the adoption of new technologies because of the difficult communications and because of the need to reach mutual agreement on investment decisions
- The company produces highly specialized products – it is not mass production

- There is no information about this technology in the region

4.3.6 Technology-specific drivers

In this chapter we focus on analysing what drivers affect the three groups of AMT. A summary by the technology group can be found in Table 12.

As we can see in the literature study, the drivers of AMT are just as diverse as the technologies themselves. Since the investments described by the case companies vary a great deal, the list of drivers also became extensive. All of these drivers described below have also been described in the literature study, in the list of drivers in the project proposal or in previous studies. The main groups of drivers for implementing AMT are:

- improve customer value
    - through better product characteristics and performance
    - through better customer service
    - improve sustainability of products and services
- improve internal process performance to
    - improve customer value, or
    - improve internal process performance, or
    - improve external processes in value network, or
    - reduce resource needs, or
    - improve sustainability of processes
- improve competitiveness
- improve financial situation and profitability

Table 12. Drivers for investment in AMT in case companies

High performance manufacturing technologies	- higher capacity - automated manufacturing - programmable manufacturing processes - automated quality control - better quality of products - more flexible production - higher quality / lower price (cost) - less waste and scrap - image as user of advanced technology
ICT-enabled intelligent manufacturing technology	- improved productivity - flexibility of process - improved speed of processes - less waste and scrap - fulfils market requirements and customer demands - improve usability of products through improved maintenance - reducing disturbance in product through better control - enabling learning from products in use

	- improved learning - enabling certification of products - enabling higher performance of products through calibration - higher efficiency of R&D processes - development of product by use of computers, - development of the products without pilot/model development - simulation of complex functions - testing and simultaneously improving the quality without any additional investments - improving financial situation
Sustainable technology	- good working environment - low energy consumption - safety - improve competitive edge through improved customer value - image issue

4.3.7 Comments on EU policy

At the end of the interviews, the interviewees were asked what the EU could do to improve the use of AMT in Europe. The comments from the interviewees are here grouped under six major topics. These are: 1) support for AMT investments, 2) managing regulation, 3) training of personnel, 4) improving competitiveness of labour force, 5) regulation of competition and 6) reducing bureaucracy.

1. Support for AMT investments
   - On a national and European level there are few policy support actions supporting investment in AMT. In regions like Singapore government is making it easier for companies to invest in automation, and in the US re-industrialization is supported through public support of investments. If there were more financial and tax promoting policies, Europe would be more competitive than it is now. Industry would have more help in improving its processes, validating new technologies and investing in new equipment and technologies.
   - European policy supports research and development, but in industry there is a need for investing in technologies which have been validated before in labs or similar industrial environments. EU could increase the speed of introducing AMT in companies through manufacturing labs available for companies at competitive prices, through know-how transmission to companies, and through incentives to invest in new technologies
   - Currently, the majority of European programmes cover technology development until TRL 7. This is a strong barrier to market for industrial companies that will have to supply AMT to manufacturers, especially if they are SMEs and they lack of own resources to cover the required investments. This reduces the efforts made in research projects by other companies, which participate in research projects in order to address the de-

velopment of new technologies, but which ultimately they are not able to buy in the market because of the lack of suppliers. New instruments that can contribute to remove this barrier – implying also a reduction of the payback time of AMT – such as Fast Track to Innovation Pilot projects, are very welcome.

- Incorporating aids or subsidies in R&D / technological innovation projects not only up to the value of the amortization during the period of the project but also for total or partial investment value in new AMT equipment.
- Delocalizing the management of EU subsidies to national or regional entities, although supervised by the EU. Some key agents could eventually take up this responsibility at a national level, i.e. The Spanish Centre for the Development of Industrial Technology (CDTI – www.cdti.es): It is a public organisation, under the Ministry of Science and Innovation whose objective is to help Spanish companies to increase their technological profile. This state-owned company was established in 1977, and since then it has financed more than 15,000 technology development projects.

2. Managing regulation
   - Perseverance is needed in taxation and other public policies. When policies are, or are perceived to be, fluctuating, entrepreneurs and managers cannot build their strategic decision and investments on existing or planned policies.
   - The regulation in Europe is often too strict and impedes the development of new technologies. The regulation in the EU needs to follow the new technological developments, and it should help to compete on equal terms with all the companies that comply with the regulatory conditions. Administrations should combat more rigorously those who do not comply with them.
   - Standards, certification and other qualification procedures should help to improve and assure products / process and to differentiate from companies that do not comply with these standards and certifications. Sustainability, environmental regulation and safety are crucial to many European companies. Especially in Sustainable Manufacturing Technologies regulations is a market driver.
   - Companies working illegally without paying taxes, selling without applying VAT, or different VAT in the different countries have a clear but uncompetitive fair advantage. This needs to be stopped.

3. Training of personnel
   - Lack of experienced personnel is a challenge to all case companies, but there are differences in what expertise the companies are lacking. While one company lacks export sales personnel, another has a lack of competent engineers. Some companies would require more expertise to assess in investing in AMT. Due to the small number of case companies analysed, we cannot say what is causing these variations in of the need for personnel.

4. Improving competitiveness of labour force
    - The competitiveness of the labour force is crucial in creating the environment for entrepreneurship and investment. More important than cutting salaries is to create an environment for efficiency and flexibility of the work force. Local agreements are needed in the labour market.

5. Regulation of competition
    - In areas such as gas, electricity and oil, there is a problem with companies having a monopolistic position in the market. They are reluctant to adopt new technologies and it is difficult for AMT providers to gain new projects in these sectors – The EU has to work more on the regulation of competition.
    - Europe should also work on entry barriers to Asian products which are a problem for European companies.
    - In new EU countries and in border region countries, there is a lack of information on suppliers and potential customers of AMT. Without good contacts with the local industry it is hard for SMEs to find customers. Thus, there is a need for more associations or clusters, which could organise workshops, seminars and brokerage events. The EU should invest more in improving this service in such developing countries in the region.
    - EU tax/custom regulation hinders trade and impairs competitiveness for companies in bordering countries.

6. Reducing bureaucracy
    - Another important factor limiting the generation of interesting innovative solutions for companies is the rigidity of the scheme of European funded projects: European projects usually last 3 – 4 years. Over 4 years, the company changes and also the technological environment evolves. During its development, the project risks becoming technologically obsolete. In this regard, the project plan becomes a major constraint because it is rigid; the contract is often perceived as a "prison" because technology development needs to look to the future, not to be stuck in the past. For the company not to have the possibility to easily change the project targets and objectives during the development is a strong barrier to the effectiveness of European funded projects. In order to overcome these barriers, it is suggested that EU projects adopt a more flexible re-modulation system that would enable it to re-shape the project concept at an intermediate point if needed. For example, there could be a mid-term project redesign option, to rethink objectives and use cases, simplifying the current amendments difficulties.

4.3.8 Conclusions from initial interviews

The interviews in the seven case companies provided an understanding of what drivers and barriers are central to these companies and interviewees. Cross-checking the answers from the general question on drivers and barriers with the answers related to specific investments shows that most of the predefined drivers/barriers groups of barriers are relevant to the companies. Arguments related to the financial situation, competitive situation and sustainability were not mentioned in the first round of answers, but the importance of these drivers/barriers was particularized in the latter part of the interviews.

In the first seven interviews, the focus was on AMT supplier companies, as five of the companies interviewed represent this group. In the next phase, focus will change to the user companies. This can bring some new understanding of the barriers and drivers for AMT investment in Europe. A larger set of cases will also enable some comparison between areas in Europe.

5 References

1. Baumers, M; Tuck, C; Wildman, R; Ashcroft, I; Rosamond, E; Hague, R. 2013. Transparency Built-in Energy Consumption and Cost Estimation for Additive Manufacturing. J. Ind. Ecol., vol. 17, JUN, pp. 418–431
2. Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Technologies. 2009 EUROPEAN MICROELECTRONICS AND PACKAGING CONFERENCE (EMPC 2009), VOLS 1 AND 2, JUN 16–18, 2009, pp. 798–809
3. Bi, ZM; Liu, YF; Baumgartner, B; Culver, E; Sorokin, JN; Peters, A; Cox, B; Hunnicutt, J; Yurek, J; O'Shaughnessey, S. 2015. Reusing industrial robots to achieve sustainability in small and medium-sized enterprises (SMEs). Ind. Robot, vol. 42, 3, pp. 264–273
4. Bond, LJ. 2015. Needs and opportunities: nondestructive evaluation for energy systems. SMART MATERIALS AND NONDESTRUCTIVE EVALUATION FOR ENERGY SYSTEMS 2015, MAR 09–10, 2015
5. Braun, T; Bauer, J; Georgi, L; Becker, KF; Koch, M; Aschenbrenner, R; Lang, KD. 2012. Enhancement of Barrier Properties of Encapsulants for Harsh Environment Applications. 2012 IEEE 62ND ELECTRONIC COMPONENTS AND TECHNOLOGY CONFERENCE (ECTC), MAY 29–JUN 01, 2012, pp. 1418–1425
6. Braun, T; Hausel, F; Bauer, J; Wittler, O; Mrossko, R; Bouazza, M; Becker, KF; Oestermann, U; Koch, M; Bader, V; Minge, C; Aschenbrenner, R; Reichl, H. 2008. Nanoparticle enhanced encapsulants for improved humidity resistance. 58TH ELECTRONIC COMPONENTS & TECHNOLOGY CONFERENCE, PROCEEDINGS, 2008, pp. 198–206
7. Camoin Associates. 2011. Research by Camoin Associates, Presentation by Robert M. Ady to the International Economic Development Council, September 18, 2011 http://www.expansionsolutionsmagazine.com/industry_articles/view/9067/understanding_advanced_manufacturing ref. 12.5.2016
8. Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, pp. 275–281
9. Chand, D., Hachey, G., Hunton, J., Owhoso, V. & Vasudevan, S. 2005. A balanced scorecard based framework for assessing the strategic impacts of ERP systems, Computers in Industry, 56, pp.558-572.
10. Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, OCT, pp. 483–489
11. Chen, HP; Xi, N. 2012. Automated Robot Tool Trajectory Connection for Spray Forming Process. J. Manuf. Sci. Eng.-Trans. ASME, vol. 134, APR
12. Chioreanu, A; Brad, S; Brad, E. 2013. Knowledge Modelling of E-maintenance in Industrial Robotics. INTERDISCIPLINARY RESEARCH IN ENGINEERING: STEPS TOWARDS BREAKTHROUGH INNOVATION FOR SUSTAINABLE DEVELOPMENT, FEB 25–MAR 01, 2013, pp. 603–610
13. Cooper, KP. 2014. Laser-based additive manufacturing: Where it has been, where it needs to go. LASER 3D MANUFACTURING, FEB 05–06, 2014
14. Cormia, RD; Oye, MM; Nguyen, A; Skiver, D; Shi, M; Torres, Y. 2014. Integrating Electron Microscopy into Nanoscience and Materials Engineering Programs. SCANNING MICROSCOPIES 2014, SEP 16–18, 2014

15. Cote, RP; Lopez, J; Marche, S; Perron, GM; Wright, R. 2008. Influences, practices and opportunities for environmental supply chain management in Nova Scotia SMEs. J. Clean Prod., vol. 16, 15, pp. 1561–1570
16. Darbanhosseiniamirkhiz, M. Ismail; W. K. W. (2012): Advanced Manufacturing Technology Adoption in SMEs: An Integrative Model, Journal of Technology Management & Innovation, Vol. 7, No. 4, pp. 112-120.
17. Das, B. 2001. Ergonomics considerations and management action in the implementation of industrial robots. Hum. Factors Ergon. Manuf., vol. 11, SUM, pp. 269–285
18. Del Rio Gonzales, P. (2005): Analysing the factors influencing clean technology adoption: a study of the Spanish pulp and paper industry, Business Strategy and the Environment, Vol. 14, No. 1, pp. 20-37.
19. Ding, H; Wijaya, K; Reissig, G; Stursberg, O. 2011. Optimizing Motion of Robotic Manipulators in Interaction with Human Operators. INTELLIGENT ROBOTICS AND APPLICATIONS, PT I: ICIRA 2011, DEC 06–08, 2011, pp. 520–531
20. Dunnebier, G. 2008. Troubleshooting and process optimisation by integrating CAPE tools and Six Sigma methodology. 18TH EUROPEAN SYMPOSIUM ON COMPUTER AIDED PROCESS ENGINEERING, JUN 01–04, 2008, pp. 943–948
21. Emmanouilidis, C; Riziotis, C. 2015. Wireless Condition Monitoring Integrating Smart Computing and Optical Sensor Technologies. ENGINEERING ASSET MANAGEMENT – SYSTEMS, PROFESSIONAL PRACTICES AND CERTIFICATION, OCT 30–NOV 01, 2013, pp. 1389–1400
22. Engeman, CD; Baumgartner, L; Carr, BM; Fish, AM; Meyerhofer, JD; Satterfield, TA; Holden, PA; Harthorn, BH. 2013. The Hierarchy of Environmental Health and Safety Practices in the US Nanotechnology Workplace. J. Occup. Environ. Hyg., vol. 10, SEP 1, pp. 487–495
23. European Commission. 2009b. Preparing for our future: Developing a common strategy for key enabling technologies in the EU COM (2009) 1257. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN
24. European Commission. 2009c. Preparing for our future: Developing a common strategy for key enabling technologies in the EU. Staff Working Paper (SEC (2009) 1257). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN ref 26.4.2016
25. European Commission. 2009d. Science, Technology and Competitiveness key figures report 2008/2009. https://ec.europa.eu/research/era/pdf/key-figures-report2008-2009_en.pdf ref 26.4.2016
26. European Commission. 2016a. EU Task Force for Advanced Manufacturing Technologies for Clean Production http://ec.europa.eu/growth/industry/innovation/advanced-manufacturing/index_en.htm ref 26.4.2016
27. European Commission. 2016b. What are KETs and why are they important? http://ec.europa.eu/growth/industry/key-enabling-technologies/description/index_en.htm ref 26.4.2016
28. European Commission. 2016c. Regional Good Practices and Pilot / Demonstrator Projects for Advanced Manufacturing https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/advanced_manufacturing/instructions ref 26.4.2016

29. Everton, S; Dickens, P; Tuck, C; Dutton, B. 2015. Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing. LASER 3D MANUFACTURING II, FEB 10–12, 2015
30. Executive Office of the President. 2011. Report to the President on Ensuring American Leadership in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2011, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf ref 26.4.2016
31. Executive Office of the President. 2012. Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2012, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf ref 26.4.2016
32. Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, pp. 35–48
33. Gerstlberger, W; Knudsen, MP; Stampe, I. 2014. Sustainable Development Strategies for Product Innovation and Energy Efficiency. Bus. Strateg. Environ., vol. 23, FEB, pp. 131–144
34. Goodrich, AC; Powell, DM; James, TL; Woodhouse, M; Buonassisi, T. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci., vol. 6, OCT, pp. 2811–2821
35. Graetz, MJ; Doud, R. 2013. TECHNOLOGICAL INNOVATION, INTERNATIONAL COMPETITION, AND THE CHALLENGES OF INTERNATIONAL INCOME TAXATION. Columbia Law Rev., vol. 113, MAR, pp. 347–445
36. Granly, BM; Webo, T. 2014. EMS and sustainability: experiences with ISO 14001 and Eco-Lighthouse in Norwegian metal processing SMEs. J. Clean Prod., vol. 64, FEB 1, pp. 194–204
37. Heyer, C. 2010. Human-Robot Interaction and Future Industrial Robotics Applications. IEEE/RSJ 2010 INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2010), OCT 18–22, 2010, pp. 4749–4754
38. Hilletofth, P; Lattila, L. 2012. Agent based decision support in the supply chain context. Ind. Manage. Data Syst., vol. 112, Sep 8, pp. 1217–1235
39. Humphrey, S; Papadopoulos, H; Linke, B; Maiyya, S; Vijayaraghavan, A; Schmitt, R. 2014. Power measurement for sustainable high-performance manufacturing processes. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, pp. 466–471
40. Irani, Z. 2002. Information systems evaluation: navigating through the problem domain. Inf. Manage., vol. 40, OCT, pp. 11–24
41. Isenberg, DJ. 2008. The Global Entrepreneur. Harv. Bus. Rev., vol. 86, DEC, pp. 107–114
42. Jansen, B; Doubrovski, EL; Verlinden, JC. 2014. Animaris Geneticus Parvus Design of a complex multi-body walking mechanism. Rapid Prototyping J., vol. 20, 4, pp. 311–319
43. Kalla, DK; Dhanasekaran, PS; Zhang, BW; Asmatulu, R. 2012. SUSTAINABILITY OF FIBER REINFORCED COMPOSITES: STATUS AND VISION FOR FUTURE. PROCEEDINGS OF THE ASME INTERNATIONAL MECHANICAL ENGINEERING CONGRESS AND EXPOSITION 2011, VOL 3, NOV 11–17, 2011, pp. 167–173
44. Khan, AS. 2014. Ethics and Nanotechnology. 2014 IEEE INTERNATIONAL SYMPOSIUM ON ETHICS IN SCIENCE, TECHNOLOGY AND ENGINEERING, MAY 23–24, 2014

45. Kohl, H; Galeitzke, M; Steinhofel, E; Orth, R. 2014. Strategic Intellectual Capital Management as a Driver of Organisational Innovation. IFKAD 2014: 9TH INTERNATIONAL FORUM ON KNOWLEDGE ASSET DYNAMICS: KNOWLEDGE AND MANAGEMENT MODELS FOR SUSTAINABLE GROWTH, JUN 11–13, 2014, pp. 1481–1495
46. Kuo, TC. 2010. The construction of a collaborative-design platform to support waste electrical and electronic equipment recycling. Robot. Comput.-Integr. Manuf., vol. 26, FEB, pp. 100–108
47. Li, BB; Chen, HP; Jin, TD. 2014. Industrial Robotic Assembly Process Modeling Using Support Vector Regression. 2014 IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2014), SEP 14–18, 2014, pp. 4334–4339
48. Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, pp. 161–178
49. Mani, M; Lyons, KW; Gupta, SK. 2014. Sustainability Characterization for Additive Manufacturing. J. Res. Natl. Inst. Stand. Technol., vol. 119, SEP 22, pp. 419–428
50. Mayer, H. O. 2006. Interview und schriftliche Befragung (Interview and written survey), Munich.
51. McFarlane, D; Giannikas, V; Wong, ACY; Harrison, M. 2013. Product intelligence in industrial control: Theory and practice. Annu. Rev. Control, vol. 37, APR, pp. 69–88
52. Meinrenken, CJ; Sauerhaft, BC; Garvan, AN; Lackner, KS. 2014. Combining Life Cycle Assessment with Data Science to Inform Portfolio-Level Value-Chain Engineering A Case Study at PepsiCo Inc. J. Ind. Ecol., vol. 18, OCT, pp. 641–651
53. Mellor, S; Hao, L; Zhang, D. 2014. Additive manufacturing: A framework for implementation. International Journal of Production Economics, vol 149, March 2014, pp. 194–201
54. Miles, M. B.; Huberman, A. M. 1994. Qualitative data analysis: An expanded sourcebook, Sage.
55. Misson, M; Zhang, H; Jin, B. 2015. Nanobiocatalyst advancements and bioprocessing applications. J. R. Soc. Interface, vol. 12, JAN 6
56. Namvar, F; Jawaid, M; Tahir, PM; Mohamad, R; Azizi, S; Khodavandi, A; Rahman, HS; Nayeri, MD. 2014. Potential Use of Plant Fibres and their Composites for Biomedical Applications. BioResources, vol. 9, 3, pp. 5688–5706
57. Nath, AK; Saha, P; Salehi-Sangari, E. 2008. Transforming supply chains in digital content delivery: A case study in apple. Research and Practical Issues of Enterprise Information Systems II, Vol 2, OCT 14–16, 2007, pp. 1079–1089
58. Neto, P. 2013. Off-line Programming and Simulation from CAD Drawings: Robot-Assisted Sheet Metal Bending. 39TH ANNUAL CONFERENCE OF THE IEEE INDUSTRIAL ELECTRONICS SOCIETY (IECON 2013), NOV 10–14, 2013, pp. 4235–4240
59. Popovic, MA; Wade, MT; Oreutt, JS; Shainline, JM; Sun, C; Georgas, M; Moss, B; Kumar, E; Alloatti, L; Pavanello, F; Chen, YH; Nammari, K; Notaros, J; Atabaki, A; Leu, J; Stojanovic, V; Ram, RJ. 2015. Monolithic Silicon Photonics in a Sub-100nm SOI CMOS Microprocessor Foundry: Progress from Devices to Systems. SILICON PHOTONICS X, FEB 09–12, 2015
60. Postek, MT; Vladar, A; Dagata, J; Farkas, N; Ming, B; Sabo, R; Wegner, TH; Beecher, J. 2008. Cellulose Nanocrystals the Next Big Nano-thing? Instrumentation, Metrology, and Standards for Nanomanufacturing II, AUG 10, 2008

61. Poston, R.; Grabski, S. 2001. Financial impacts of enterprise resource planning implementations, International Journal of Accounting Information Systems, 2, pp.271-294.
62. Priarone, PC; Robiglio, M; Settineri, L; Tebaldo, V. 2015. Effectiveness of minimizing cutting fluid use when turning difficult-to-cut alloys. 22ND CIRP CONFERENCE ON LIFE CYCLE ENGINEERING, APR 07–09, 2015, pp. 341–346
63. Ramamoorthy, SK; Skrifvars, M; Persson, A. 2015. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. Polym. Rev., vol. 55, JAN 2, pp. 107–162
64. Rangan, RM; Rohde, SM; Peak, R; Chadha, B; Bliznakov, P. 2005. Streamlining product lifecycle processes: a survey of product lifecycle management implementations, directions, and challenges. J. Comput. Inf. Sci. Eng., vol. 5, SEP, pp. 227–237
65. Ren, X; Zhang, QW; Liu, KW; Li, HL; Zhou, JG. 2014. Modeling of pneumatic valve dispenser for printing viscous biomaterials in additive manufacturing. Rapid Prototyping J., vol. 20, 6, pp. 434–443
66. Rogers, E. M. 2003. Diffusion of innovations, New York: Free Press
67. Romig, AD. 2004. Nanotechnology: Scientific challenges and societal benefits and risks. Metall. Mater. Trans. A-Phys. Metall. Mater. Sci., vol. 35A, DEC, pp. 3641–3648
68. Ruhnau, T; Bunzel, WM. 2014. Sustainability in Automotive Pricing. SUSTAINABLE AUTOMOTIVE TECHNOLOGIES 2013, SEP 25–27, 2013, pp. 143–150
69. Science and Technology Policy Institute. 2010. White Papers on Advanced Manufacturing Questions. https://www.whitehouse.gov/sites/default/files/microsites/ostp/advanced-manuf-papers.pdf ref 26.4.2016
70. Secundo, G; Passiante, G; Romano, A; Moliterni, P. 2013. Developing the Next Generation of Engineers for Intelligent and Sustainable Manufacturing: A Case Study. Int. J. Eng. Educ, vol. 29, 1, pp. 248–262
71. Shukor, SA; Axinte, DA. 2009. Manufacturability analysis system: issues and future trends. Int. J. Prod. Res., vol. 47, 5, pp. 1369–1390
72. Sidambe, AT. 2014. Biocompatibility of Advanced Manufactured Titanium Implants – A Review. Materials, vol. 7, DEC, pp. 8168–8188
73. Singh, B; Sewell, N. 2012. Knowledge based process planning and design for Additive Manufacturing (KARMA). INNOVATIVE DEVELOPMENTS ON VIRTUAL AND PHYSICAL PROTOTYPING, SEP 28–OCT 01, 2011, pp. 619–624
74. Spathis, C; Constantinides, S. 2003. The usefulness of ERP systems for effective management, Industrial Management and Data Systems, 103(9), pp. 677-685.
75. Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from integrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, pp. 1311–1316
76. Tornatzky, L; Fleischer, M. 1990. The process of technology innovation, Lexington, MA: Lexington Books
77. Ulewicz, S; Schutz, D; Vogel-Heuser, B. 2014. Integration of Distributed Hybrid Multi-Agent Systems into an Industrial IT Environment. 2014 12TH IEEE INTERNATIONAL CONFERENCE ON INDUSTRIAL INFORMATICS (INDIN), JUL 27–30, 2014, pp. 519–525

78. Vaia, RA. 2012. Nanomaterials and Future Aerospace Technologies: Opportunities and Challenges. MICRO- AND NANOTECHNOLOGY SENSORS, SYSTEMS, AND APPLICATIONS IV, APR 23–27, 2012
79. Venkatasubramanian, V. 2005. Prognostic and diagnostic monitoring of complex systems for product lifecycle management: Challenges and opportunities. Comput. Chem. Eng., vol. 29, MAY 15, pp. 1253–1263
80. Vezzoli, C; Ceschin, F; Diehl, JC; Kohtala, C. 2015. New design challenges to widely implement 'Sustainable Product-Service Systems'. J. Clean Prod., vol. 97, JUN 15, pp. 1–12
81. Wang, ED; Yuan, C. 2014. A hybrid life cycle assessment of atomic layer deposition process. J. Clean Prod., vol. 74, JUL 1, pp. 145–154
82. Wang, Y; Chen, Y; Benitez-Amado, J. 2015. How information technology influences environmental performance: Empirical evidence from China. Int. J. Inf. Manage., vol. 35, APR, pp. 160–170
83. Yang, SH; Bagheri, B; Kao, HA; Lee, J. 2015. A Unified Framework and Platform for Designing of Cloud-Based Machine Health Monitoring and Manufacturing Systems. J. Manuf. Sci. Eng.-Trans. ASME, vol. 137, AUG
84. Yin, R. K. 2003. Case studies research: design and methods, Thousand Oaks, Sage.
85. Yoo, DJ. 2014. Recent Trends and Challenges in Computer-Aided Design of Additive Manufacturing-based Biomimetic Scaffolds and Bioartificial Organs. Int. J. Precis. Eng. Manuf., vol. 15, OCT, pp. 2205–2217
86. Zhang, XY; Zhang, YD. 2015. Tissue Engineering Applications of Three-Dimensional Bioprinting. Cell Biochem. Biophys., vol. 72, JUL, pp. 777–782
87. Zhang, YF; Wang, WB; Liu, SC; Xie, GN. 2014. Real-Time Shop-Floor Production Performance Analysis Method for the Internet of Manufacturing Things. Adv. Mech. Eng.
88. Zhao, QQ; Boxman, A; Chowdhry, U. 2003. Nanotechnology in the chemical industry – opportunities and challenges. J. Nanopart. Res., vol. 5, DEC, pp. 567–572European Commission. 2009a. A Strategy for ICT R&D and Innovation in Europe: Raising the Game COM (2009) 116. http://eur-lex.europa.eu/legal-content/EN/ TXT/ PDF/?uri=CELEX:52009DC0116&from=EN

Annex

Annex I. Drivers and barriers to AMT – literature study

DRIVERS AND BARRIERS TO AMT – LITERATURE STUDY

CONTENT

1 ICT-enabled intelligent manufacturing

1.1 Environmental context

1.1.1 Innovation management

Technological innovation is regarded as a key constituent for economic growth. It follows that nations strive to stimulate and attract the research and development (R&D) and to make themselves hospitable environments for the holding of intellectual property (IP). “Tax policies have taken centre-stage in nations’ efforts to accomplish these goals and to capture a share of the income from technological innovations. Designing cost-effective methods of supporting technological innovations has, however, become substantially more difficult as the world economy has become more interconnected. Where R&D is performed and where income is earned change in response to the nature and level of government support. The capacity of multinational enterprises (”MNEs”) to shift their IP production, IP ownership, and IP income across national borders, along with their ability to establish new corporations in tax-favourable jurisdictions, makes designing cost-effective incentives exceptionally difficult. Devising appropriate tax rules for developing IP and for taxing IP income has become the central challenge for international income taxation” (Graetz and Doud, 2013)[48]. Graetz and Doud (2013) “examine the three primary tax policies supporting innovation: (1) incentives for R&D, (2) ”patent boxes”, and (3) tax benefits for ”advanced manufacturing.” It then briefly describes common techniques that MNEs use to lower their taxes on IP income. Based on extensive examination of the economic evidence, Graetz and Doud (2013) conclude that, at most, only R&D incentives are justified”[49].

Harvard professor Isenberg (2008) has found that global start-ups face three major challenges. First are the problems and barriers created by distance and by differences in culture and economic development levels. Second challenge is to manage the context – that is, the different nations’ political, regulatory, judicial, tax, and labour environments. Third, start-ups must compete with bigger companies while using far fewer resources. To succeed, Isenberg has found, global entrepreneurs must develope four competences: to clearly articulate reasons for going global, to build alliances with powerful partners, to manage the international supply chain, and to create a multinational culture in their organization.

The next generation of advanced manufacturing technologies must rely on cooperation and collaboration of business partners to share costs, risks and expertise. No single company has

[48] Graetz, MJ; Doud, R. 2013. Technological innovation, international competition, and the challenges of international income taxation. Columbia Law Rev., vol. 113, MAR, page 347 [60]

[49] Ibidem.

all the expertise needed to manage sophisticated and frequently changing demands from customers, global competition and technological advances. “To respond to these challenges, development of an effective scheme for managing collaborative workflows is required.”[50] Hsieh and Lin (2014) “propose a framework to achieve coherent and consistent workflows that can meet order requirements based on multi-agent systems (MAS). Scheduling collaborative workflow is a challenging problem due to the computational complexity involved, distributed architecture and dependency of different partners’ workflows”[51] (Hsieh and Lin, 2014).

1.1.2 Advanced information systems

There is a great deal of difficulty when it comes to the evaluation of investments in information systems, with companies often finding themselves unable to assess the full implications of their IS infrastructure. Many of the savings resulting from information systems are considered suitable for inclusion within traditional accountancy frameworks. However, it is the intangible and non-financial benefits, together with indirect project costs that complicate the justification process. Irani (2002) presents problems experienced during attempts to evaluate, implement, and realize the holistic implications of the information system investment. Tabanli and Ertay (2013) “present a case study about deployment of the radio frequency identification (RFID) technology-based electronic Kanban system in an automotive industry supplier firm. To evaluate the return on the investment, performance metrics were established and a benefit-cost analysis is carried out. Obviously, future gains will include better inventory management to reduce the inventory levels within the production system”.[52]

According to Zhang et al. (2014) “typical challenges that manufacturing enterprises are now facing are compounded by a lack of timely, accurate, and consistent information of manufacturing resources. As a result, it is difficult to analyse the real-time production performance for the shop-floor.”[53] The authors “provide a new paradigm by extending the techniques of the internet of things (IoT) to manufacturing field. Under this architecture, the real-time primitive events which occurred at different manufacturing things such as operators, machines, pallets, key materials, and so forth can easily be sensed. Based on these distributed primitive events, a

[50] Hsieh, FS; Lin, JB. 2014. A Multiagent Approach for Managing Collaborative Workflows in Supply Chains. Proceedings of the 2014 IEEE 18th International Conference on Computer Supported Cooperative Work in Design (CSCWD), May 21–23, 2014, page 71 [68]

[51] Ibidem.

[52] Tabanli, RM; Ertay, T. 2013. Value stream mapping and benefit-cost analysis application for value visibility of a pilot project on RFID investment integrated to a manual production control system-a case study. Int. J. Adv. Manuf. Technol., vol. 66, May, page 987 [137]

[53] Zhang, YF; Wang, WB; Liu, SC; Xie, GN. 2014. Real-Time Shop-Floor Production Performance Analysis Method for the Internet of Manufacturing Things. Adv. Mech. Eng. page 1 [158]

critical event model is established to automatically analyse the real-time production performance."[54]

Sztipanovits et al. (2014) "describe the challenges of and solution approaches to building a comprehensive design tool suite for complex Cyber-Physical Systems. The primary driver was to reduce significantly the costly design-build-test-redesign cycles in design flows."[55] Model- and component-based design has yielded a dramatic increase in design productivity in several narrowly focused homogeneous domains, such as signal processing, control and aspects of electronic design. "However, a significant impact on the design and manufacturing of complex cyber-physical systems (CPS) such as vehicles has not yet been achieved."[56] Sztipanovits et al. (2014) "focus on the impact of heterogeneity in modelling CPS. This challenge is compounded by the need to rapidly evolve the design flow by changing/updating the selection of modelling languages, analysis and verification tools and synthesis methods."[57]

As an example, Ngai et al. (2012) "identify eight factors for the successful implementation of an RFID-based manufacturing process management system, namely: vendor selection, organisational motivation, cost/benefit evaluation, top management support, user involvement, the extent of progress supervision, staff competence and training, and policy, structure and operating process compatibility."[58] Ngai et al. (2012) "detail the organisation's experience and identifies the challenges it faces and important issues in the development and implementation of the system."[59]

1.1.3 Supply chain management

An important competitive tool in the manufacturing industry is agility, or the ability to respond quickly and effectively to market demands. Firms deploying global sourcing strategies have to balance the benefits of cost-effectiveness against the limitations of off shore production, that is, reduced agility. "Improving supply chain performance is a key to achieving cost effectiveness, and the improvement largely depends on the degree to which uncertainty can

---

[54] Zhang, YF; Wang, WB; Liu, SC; Xie, GN. 2014. Real-Time Shop-Floor Production Performance Analysis Method for the Internet of Manufacturing Things. Adv. Mech. Eng. page 1 [158]

[55] Sztipanovits, J; Bapty, T; Neema, S; Howard, L; Jackson, E. 2014. OpenMETA: A Model- and Component-Based Design Tool Chain for Cyber-Physical Systems. From programs to systems: the systems perspective in computing, Apr 06, 2014, page 235 [136]

[56] Ibidem

[57] Ibidem

[58] Ngai, EWT; Chau, DCK; Poon, JKL; Chan, AYM; Chan, BCM; Wu, WWS. 2012. Implementing an RFID-based manufacturing process management system: Lessons learned and success factors. J. Eng. Technol. Manage., vol. 29, JAN–MAR, page 112 [106]

[59] Ibidem.

be reduced in the supply chain."[60] Nath, Saha and Salehi-Sangari (2007) "conduct a case study of Apple as it moves into the arena of digital content delivery and initiates hardware innovations in an industry that is characterized by increasing product variety, new technologies, price erosion, and fast inventory turn-overs. The purpose is to explore Apple's supply chain and some of the challenges it has faced in agilely managing its offshore manufacturing in facing demand."[61]

Nath, Saha and Salehi-Sangari (2007) also "explore the manoeuvring, shift of power and change of roles within the supply chain as it moves into the arena of digital content delivery"[62]. As a result of their study, Nath, Saha and Salehi-Sangari reach the conclusion that "successful companies stand to face the dual task of changing the mindset of its suppliers on the one hand, and meeting and setting up an uncharted path for its customers in digital content in a pioneering role for the industry on the other."[63] They find that, "while managing the supply chain in the traditional 'non-e' market provides challenges related to cost-effectiveness and physical barriers, in the 'e' marketplace managing the supply chain encounters barriers not physical but rather strategic that is entrenched in more traditional operating modes." [64]

1.2 Organizational context

1.2.1 Innovation management

The importance of intangible resources for business success is increasing and is often assessed higher than the impact of tangible resources. "Analyses have indicated some intellectual capital factors as the most prominent and important, yet the impact on the intra- and inter-organizational innovation ecosystems has not been analysed thoroughly. Although the most important factors of intellectual capital are identified, the specific drivers of innovation have not been investigated."[65] Kohl et al. (2014) seek "to close this gap and draw meaningful conclusions with regard to drivers of innovation and related differences between manufacturing and service enterprises. The analysis of the correlation between intellectual capital and innovation capabilities allows statements regarding the intellectual capital factors, on which enterprises should be focused in order to foster innovation" [18] (Table 1) (Kohl et al, 2014).

---

[60] Nath, AK; Saha, P; Salehi-Sangari, E. 2008. Transforming supply chains in digital content delivery: A case study in apple. Research and Practical Issues of Enterprise Information Systems II, Vol 2, Oct 14–16, 2007, page 1079 [103]
[61] Ibidem.
[62] Idem, page 1080 [103]
[63] Ibidem.
[64] Idem, page 1079 [103]
[65] Kohl, H; Galeitzke, M; Steinhofel, E; Orth, R. 2014. Strategic Intellectual Capital Management as a Driver of Organisational Innovation. IFKAD 2014: 9th International Forum on Knowledge Asset Dynamics: Knowledge and Management Models for Sustainable Growth, Jun 11–13, 2014, page 2 [78]

Table 1. Success factors of intellectual capital (source: Kohl et al, 2014[66])

Standard Success Factors for Human Capital	
• Professional Competence	Human Capital includes the staff's competences, skills, attitudes and the employee's motivation. Human Capital is owned by the employee and can be taken home or on to the next employer.
• Social Competence	
• Employee Motivation	
• Leadership Ability	
Standard Success Factors for Structural Capital	
• Internal Co-operation and Knowledge Transfer	Structural Capital comprises all structures and processes needed by the employee in order to be productive and innovative. It consists of those intangible structures which remain with the organisation when the employee leaves.
• Management Instruments	
• Information Technology and Explicit Knowledge	
• Product Innovation	
• Process Optimisation and Innovation	
• Corporate Culture	
Standard Success Factors for Relational Capital	
• Customer Relationships	Relational Capital sums up all relationships to external groups and persons established by the organization, e.g. customers, suppliers, partners and the public.
• Supplier Relationships	
• Public Relationships	
• Investor Relationships	
• Relation to Co-operation Partners	

Winter, Ronkko and Rissanen (2014) illustrate problems with organizational barriers-"when working with software engineering tasks and usability requirements."[67] The article "deals with a large company that manufactures industrial robots with an advanced user interface, which wanted to introduce usability KPIs so as to improve product quality. The situation in the company makes this difficult, due to a combination of organizational and behavioural factors that led to a "wicked problem" that caused conflicts, breakdowns and barriers."[68]

In another case, the researcher was presented with resistance to change; difficulties in managing the expectations of non-technologically driven management; and difficulties with balancing the development of the strategic goals with pressures for commercial output. The objective was to implement a sophisticated CAD package in a small company that produces luxury motor yachts. "The strategic aim was to bring the 1000+ components into the CAD environment, supporting each component with procurement information. The intention was that this would lead to reduced design cycle times through the development of parts libraries; im-

[66] Kohl, H; Galeitzke, M; Steinhofel, E; Orth, R. 2014. Strategic Intellectual Capital Management as a Driver of Organisational Innovation. IFKAD 2014: 9th International Forum on Knowledge Asset Dynamics: Knowledge and Management Models for Sustainable Growth, Jun 11–13, 2014, page 8 [78]

[67] Winter, J; Ronkko, K; Rissanen, M. 2014. Identifying organizational barriers – A case study of usability work when developing software in the automation industry. J. Syst. Softw., vol. 88, Feb, page 54 [150]

[68] Ibidem

proved efficiencies in planning boat-building; and, reduced manufacturing cycle times"[69] through improved drawings with relevant supporting information (Walters and Millward, 2011). "In a small commercial environment such a strategic development presents a challenging task."[70] Walters and Millward's case study highlights the difficulties that can arise when ambitious technology implementation plans that impact on various business functions, are developed in an active commercial environment with limited labour resources (Walters and Millward, 2011).

1.2.2 Advanced information systems

Product lifecycle management (PLM) systems have been heavily invested in during the past three decades. PLM processes span "all product lifecycle phases from requirements definition, systems design/ analysis, and simulation, detailed design, manufacturing planning, production planning, quality management, customer support, in-service management, and end-of-life recycling. Initiatives ranging from process re-engineering, enterprise-level change management, standardization, globalization and the like have moved PLM processes to mission-critical enterprise systems."[71] "However, the need to optimize organization processes rather than individual benefits poses challenging culture change management issues and have derailed many enterprise-scale PLM efforts"[72] (Rangan et al, 2005).

Venkatasubramanian (2005) has studied the lifecycle of complex systems. "In the discrete parts industries, such as the auto industry, many product malfunctions are due to unanticipated dynamic interactions due to a repeated use or misuse of components. These interactions thrive in complex systems when the combined effects of uncertainty and operational adversity are not properly addressed either in design or in operation. Given the size, scope and complexity of the systems and interactions, it is becoming increasingly difficult for plant personnel to anticipate, diagnose and control serious abnormal events in a timely manner. Hence, it should come as no surprise that human operators tend to take erroneous decisions and take actions which make matters even worse, as reported in the literature"[73] (Venkatasubramanian, 2005).

---

[69] Walters, AT; Millward, H. 2011. Challenges in managing the convergence of information and product design technology in a small company. Int. J. Technol. Manage., vol. 53, Apr 2, page 190 [147]

[70] Walters, AT; Millward, H. 2011. Challenges in managing the convergence of information and product design technology in a small company. Int. J. Technol. Manage., vol. 53, Apr 2, page 190 [147]

[71] Rangan, RM; Rohde, SM; Peak, R; Chadha, B; Bliznakov, P. 2005. Streamlining product lifecycle processes: a survey of product lifecycle management implementations, directions, and challenges. J. Comput. Inf. Sci. Eng., vol. 5, Sep, page 227 [116]

[72] Ibidem.

[73] Venkatasubramanian, V. 2005. Prognostic and diagnostic monitoring of complex systems for product lifecycle management: Challenges and opportunities. Comput. Chem. Eng., vol. 29, May 15, page 1253 [144]

Indeed, “the pace of economic, social and technological change has increased the gap between the competences needed by industry and those provided by the universities’ curricula”[74] (Secundo et al, 2013). Companies in high-tech have found it difficult to get skilled labour, especially with industry-specific experience. “Training for a broad range of skills and practice is challenging, especially for community colleges. Workforce studies (SRI/Boeing) suggest that even four-year colleges often do not provide the relevant training and experience in laboratory skills, especially design of experiments and analysis of data”[75] (Cormia et al, 2014). “This requires an increasingly integrated approach by academia and industry in order to afford the problem of the obsolescence of engineering competences.”[76] Secundo et al. (2013) “address the needs for providing manufacturing education to meet the challenges in terms of ”who’’-the profile for the next generation of manufacturing engineer; ”what’’-the new system for education and its contents, and ”how’’-innovative learning approaches and strategy to incentive the development of competence.”[77]

Resource planning

Company management is often faced with the challenge to determine the performance benefits their firm can gain from use of enterprise resource planning (ERP) systems, and to identify the factors that contribute to success. Hart and Snaddon (2014) compile a list of expected ERP benefits and critical success factors (CSFs). “Although a core list of CSFs is identified, and three associations are found between CSFs and ERP benefits, Hart and Snaddon (2014) conclude that further research is needed”.[78]

---

[74] Secundo, G; Passiante, G; Romano, A; Moliterni, P. 2013. Developing the Next Generation of Engineers for Intelligent and Sustainable Manufacturing: A Case Study. Int. J. Eng. Educ, vol. 29, 1, page 248 [125]

[75] Cormia, RD; Oye, MM; Nguyen, A; Skiver, D; Shi, M; Torres, Y. 2014. Integrating Electron Microscopy into Nanoscience and Materials Engineering Programs. SCANNING MICROSCOPIES 2014, SEP 16–18, 2014, page 92360N-1 [28]

[76] Secundo, G; Passiante, G; Romano, A; Moliterni, P. 2013. Developing the Next Generation of Engineers for Intelligent and Sustainable Manufacturing: A Case Study. Int. J. Eng. Educ, vol. 29, 1, page 248 [125]

[77] Ibidem.

[78] Hart, CA; Snaddon, DR. 2014. The organisational performance impact of erp systems on selected companies. S. Afr. J. Ind. Eng., vol. 25, MAY, pp. 14–28, page 14 [63]

Table 2. Expected enterprise resource planning benefits (source: Hart and Snaddon, 2014)[79]

Source of Information	Literature Analysis	Literature Analysis	Literature Analysis	Literature Analysis	Survey	Case Studies	Literature & Case Studies	Case Studies	Case Studies	Case Studies	
Benefit / Author	Siriginidi (2000)	Nah et al (2001)	Chand et al (2005)	Poston & Grabski (2001)	Spathis & Constanti-nides (2003)	Sarkis & Sundarraj (2000)	Shang & Seddon (2002)	Davenport (1998)	Mandal & Gunasek-aran (2003)	Gupta & Kohli (2004)	Rank
Improved accuracy & timeliness of information	✓	✓	✓	✓	✓			✓	✓		A
Improved information sharing		✓		✓	✓			✓	✓	✓	A
Improved business processes	✓	✓	✓	✓					✓	✓	A
Increased integration of applications		✓	✓		✓	✓	✓				A
Improved decision-making			✓	✓	✓		✓			✓	A
Reduced operating and admin costs		✓	✓	✓	✓		✓				A
Reduced stock levels	✓	✓	✓		✓						B
Increased business/sales	✓			✓		✓	✓				B
Reduced cycle times	✓	✓		✓			✓				B
Improved customer service	✓			✓		✓	✓				B
Improved productivity and efficiencies				✓			✓	✓		✓	B
Improved on-time shipments	✓				✓			✓			B
Reduced IT operating costs			✓		✓		✓				B
Reduced data processing time			✓		✓			✓			B
Reduced lead times	✓					✓					C
Increased inventory turns	✓				✓						C
Reduced quality costs/quality improvement	✓						✓				C
Improved vendor performance	✓			✓							C
Improved resource utility	✓										C
Increased user friendliness of IS					✓						C
Adherence to best practice work patterns							✓				C
Organisational learning							✓				C
Effectiveness of employees							✓				C
Roll out of a common vision							✓				C

Usually, ERP implementation failures are the result of business problems rather than technical difficulties. ERP systems affect a firm's strategy, organization, and culture. Yen and Sheu (2004) investigate the relationship between ERP implementation and the firm's competitive strategy.

---

[79] Hart, CA; Snaddon, DR. 2014. The organisational performance impact of erp systems on selected companies. S. Afr. J. Ind. Eng., vol. 25, MAY, pp. 14–28, page 17 [63]

The results “confirm that ERP implementation should be aligned with competitive strategy. Specific guidelines are suggested for making the alignment.”[80]

Enterprise resource planning (ERP) systems have become useful instruments for managing multinational operations. Barriers to transnational trade and investment have been lowered due to globalization, and information and communication technologies have improved. Hence, multinational firms can conduct operations with increased ease and utilize cost-advantageous production resources. Notably, ERP systems “integrate information platforms to reflect operations at each operation point in real time and generate information as a basis for decision-making and resource allocations”[81] (Chou and Hong, 2013). Yen and Sheu (2004) identify “two other variables, national culture and government/corporate policies, as being critical to ERP implementation in multinational settings.”[82]

1.2.3 Supply chain management

Fawcett, Magnan and McCarter (2008) argue that the people issues, such as culture, trust, aversion to change, and willingness to collaborate, are the key bridge to successful collaborative innovation and should, therefore, not be overlooked as companies invest in supply chain enablers such as technology, information, and measurement systems. They provide new insight into understanding the success and hindering factors of supply chain management. Fawcett, Magnan and McCarter’s (2008) “macro picture of the goals, challenges, and strategies for implementing supply chain management”[83] is presented in Figure 1.

[80] Yen, HR; Sheu, C. 2004. Aligning ERP implementation with competitive priorities of manufacturing firms: An exploratory study. Int. J. Prod. Econ., vol. 92, DEC 18, 2004, page 207 [154]

[81] Chou, JS; Hong, JH. 2013. Assessing the impact of quality determinants and user characteristics on successful enterprise resource planning project implementation. J. Manuf. Syst., vol. 32, OCT, page 792 [23]

[82] Yen, HR; Sheu, C. 2004. Aligning ERP implementation with competitive priorities of manufacturing firms: An exploratory study. Int. J. Prod. Econ., vol. 92, DEC 18, page 207 [154]

[83] Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, page 35 [53]

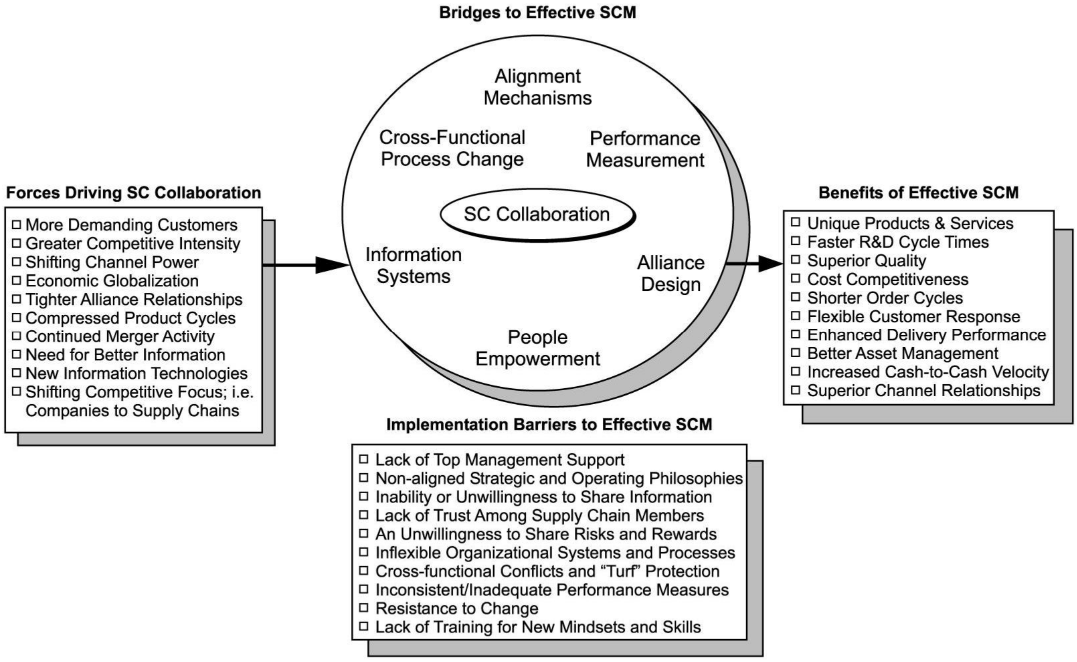


Figure 1. A contingency framework for understanding supply chain implementation (source: Fawcett et al, 2008[84])

Blackman, Holland and Westcott (2013) define and explore the concept of financial supply chain strategy in a global business environment. They illustrate the concepts with a detailed case study of Motorola's global financial supply chain. "The financial supply chain is an integral component of Motorola's overall supply chain management strategy. Physical product, information systems and financial flows are closely aligned with each other throughout the supply chain incorporating Motorola, its customers, suppliers and banks. The overall trend is towards the development of an integrated global financial supply chain in which cash flows mirror product flows. Motorola shares financial data with its suppliers as part of a cooperative strategy that generates cost savings for Motorola and its suppliers in areas such as foreign exchange and cash balances. The cooperative strategy also improves the quality of the payments process measured by six sigma techniques and produces strategic benefits such as risk reduction for the supply chain as a whole in areas such as foreign exchange and payments. A strategy of this type is only possible by taking a global perspective of the financial supply chain."[85]

Blackman, Holland and Westcott (2013) conclude that "the development of integrated financial supply chains will lead to significant savings in terms of funding, banking and administra-

[84] Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, page 37 [53]

[85] Blackman, ID; Holland, CP; Westcott, T. 2013. Motorola's global financial supply chain strategy. Supply Chain Manag., vol. 18, 2, page 132 [6]

tive costs associated with treasury and payment activities. The implementation and nature of the strategic change also highlight important strategic planning and implementation issues associated with financial supply chains"[86] (Blackman et al, 2013).

1.3 Technological context

1.3.1 Innovation management

Colledani et al. (2014) propose production quality as a new paradigm aiming at going beyond traditional six-sigma approaches. "This new paradigm is extremely relevant in technology-intensive and emerging strategic manufacturing sectors, such as aeronautics, automotive, energy, medical technology, micro-manufacturing, electronics and mechatronics. The traditional six-sigma techniques show strong limitations in highly changeable production contexts, characterized by small batch productions, customized, or even one-of-a-kind products, and in-line product inspections. Innovative and integrated quality, production logistics and maintenance design, management and control methods as well as advanced technological enablers play a key role in achieving the overall production quality goal."[87] Colledani et al. (2014) "revise problems, methods and tools to support this paradigm and highlight the main challenges and opportunities for manufacturing industries in this context."[88]

Similarly, McFarlane et al. (2013) explore "the evolving industrial control paradigm of product intelligence. The approach seeks to give a customer greater control over the processing of an order – by integrating technologies which allow for greater tracking of the order and methodologies which allow the customer to dynamically influence the way the order is produced, stored or transported."[89] McFarlane et al. (2013) examine "developments from four distinct perspectives: conceptual developments, theoretical issues, practical deployment and business opportunities." They conclude "by identifying four key obstacles to be overcome in order to successfully deploy product intelligence in an industrial application."[35] These are "(i) the modelling of intelligent products, (ii) the language required for an intelligent product to communicate, (iii) the architecture which specifies the functionality of the intelligent product and

---

[86] Blackman, ID; Holland, CP; Westcott, T. 2013. Motorola's global financial supply chain strategy. Supply Chain Manag., vol. 18, 2, page 132 [6]

[87] Colledani, M; Tolio, T; Fischer, A; Iung, B; Lanza, G; Schmitt, R; Vancza, J. 2014. Design and management of manufacturing systems for production quality. CIRP Annals – Manufacturing Technology. CIRP Ann-Manuf. Technol., vol. 63, 2, page 773 [25]

[88] Ibidem.

[89] McFarlane, D; Giannikas, V; Wong, ACY; Harrison, M. 2013. Product intelligence in industrial control: Theory and practice. Annu. Rev. Control, vol. 37, Apr, page 69 [97]

determines how it interacts with its environment, and (iv) the algorithms used by an intelligent product to support its decision-making process."[90]

There are more and more technological tools available for the realisation of intelligent products. However, there are still some challenges that need to be tackled before their deployment in real industrial systems. McFarlane et al. (2013) comment on "three classes of these challenges:

- Technical feasibility: Many of the building blocks for supporting product intelligence are either in place or under development. However, a major outstanding obstacle is that of demonstrating that an intelligent product environment can be deployed with industrial scale information systems. Other open issues are the specification of open, standard, user-friendly and widely-accepted interfaces, the specification of what information is gathered, stored and distributed and how it is managed during the product's lifecycle, the development of software systems that will use the available information effectively, as well as the development of appropriate hardware for the realisation of the on-board intelligence.
- Operational practicality: Initial deployments are likely to be partial rather than full deployments and hence validating the compatibility of any such development with other necessary information systems is something that has been characterised as a major issue for the success of intelligent products. In the longer term, when active deployments are considered on a commercial scale, the stability of operation of what are potentially highly distributed systems must be considered.
- Decision execution: In many cases, software alone cannot directly cause actions in the real world without interfacing with actuators, transportation systems and sometimes human operators. Thus, although the decision might be automated and less labour-intensive, we need to think about what is needed to effectively (and ideally automatically) translate that decision into real-world actions, both from a technical perspective and from the perspective of a compelling business model."[91]

1.3.2 Advanced information systems

Manufacturability analysis and optimization

The manufacturing sector has been slow in incorporating analytics in their strategic decision making. However, "the situation is changing with increasing use of analytics for product devel-

---

[90] McFarlane, D; Giannikas, V; Wong, ACY; Harrison, M. 2013. Product intelligence in industrial control: Theory and practice. Annu. Rev. Control, vol. 37, Apr, page 76 [97]

[91] Idem, page 82 [97]

opment, operations and logistics."[92] Recent advances in simulation optimization research and more powerful computers have made it possible to optimize complex stochastic systems that are otherwise intractable. Dutta and Bose (2015) investigate an entire Big Data process, and conclude "that a clear understanding of the business problem, a detailed and well planned step-by-step project map, a cross functional project team, adoption of innovative visualization techniques, patronage and active involvement of top management and a culture of data driven decision making are essential for the success of a Big Data project"[93] (Dutta and Bose, 2015). Xu et al. (2015) discuss how simulation optimization can benefit from cloud computing and high-performance computing, its integration with big data analytics, and the value of simulation optimization to help address challenges in engineering design of complex systems. They use health care, logistics and manufacturing systems as their case examples of simulation optimizations.

If design and manufacturing activities take place sequentially rather than simultaneously, there may occur inefficient and time consuming iterations between these two stages. In order to expedite these iterations, "manufacturability analysis systems (MASs) have been developed to allow the evaluation of various manufacturability aspects during the design stage and consequently to reduce the costs and time to market of the designed products."[94] Shukor and Axinte (2009) conclude "with discussion and suggestions for some prospective research trends and challenges in building and exploiting MASs. Particular attention is paid to the application of a MAS to micro-manufacturing processes on which, nowadays, both academics and industry are focusing their attentions for identifying future research and technological challenges and opportunities."[40]

However, "even though different communication concepts have been developed and are provided within a MAS architecture, connections to other industrial IT systems such as Enterprise Resource Planning (ERP) or third party MAS implementations have not been included. To enable maximizing the system's flexibility, a complete immersion of the MAS into the industrial IT environment needs to be provided" [95] (Ulewicz et al, 2014). Silcher et al. (2013) argue that companies' IT systems "are typically isolated, and their communication, cooperation and in special cases also integration results in increasing overheads and quickly becomes unmanageable. Further problems arise, when building continuous processes within the Product Lifecy-

---

92 Dutta, D; Bose, I. 2015. Managing a Big Data project: The case of Ramco Cements Limited. Int. J. Prod. Econ., vol. 165, Jul, page 293 [36]

93 Ibidem.

94 Shukor, SA; Axinte, DA. 2009. Manufacturability analysis system: issues and future trends. Int. J. Prod. Res., vol. 47, 5, 2007, page 1369 [129]

95 Ulewicz, S; Schutz, D; Vogel-Heuser, B. 2014. Integration of Distributed Hybrid Multi-Agent Systems into an Industrial IT Environment. 2014 12th IEEE International Conference On Industrial Informatics (INDIN), Jul 27–30, 2014, page 519 [1401]

cle Management (PLM). They propose a service-based PLM architecture faces these challenges and presents a homogeneous integration approach based on Enterprise Service Bus (ESB) technology."[96]

1.3.3 Supply chain management

Hilletofth and Lättilä (2012) investigate the benefits of and the barriers to agent-based decision support (ABDS) systems in the supply chain context. The benefits of ABDS systems include "the possibility to increase the versatility of system architecture, to improve supply chain visibility, to conduct experiments and what-if analyses, to improve the understanding of the real system, and the possibility to improve communication within and between organizations in the supply chain. The barriers to ABDS systems in the supply chain context include the difficulty of accessing data from partners in the supply chain, the difficulty of accessing data on a higher level of granularity, and the difficulty of retrieving data from other information systems."[97]

Order follow-up and inventory management

Radio-Frequency Identification RFID technology is used more and more in supply chain processes. "It can be in manufacturing, material handling, warehousing, etc. Using RFID has multiple considerable advantages such as batch readability, process capability, information storage, and resistance to harsh environments"[98] (Ghelichi and Abdelgawad, 2014). Ghelichi and Abdelgawad (2014) discuss inventory management and its importance for a firm. The study evaluates the opportunity of using RFID in inventory management over traditional method with more details to grasp what the impact of using this technology is on inventory management over traditional methods. Similarly, Dias et al. (2009) "forecast the use of RFID technologies integrated into an information and communication technologies (ICT) framework based on distributed artificial intelligence (DAI) supported by a multi-agent system (MAS), as the greatest value advantage of supply chain management (SCM) in a cooperative intelligent logistics systems. Logistical platforms (production or distribution) as nodes of added value of supply and distribution networks are proposed as critical points of the visibility of the inventory, where these technological needs are more evident."[99]

---

[96] Silcher, S; Dinkelmann, M; Minguez, J; Mitschang, B. 2013. Advanced Product Lifecycle Management by Introducing Domain-Specific Service Buses. Enterprise Information Systems, ICEIS 2012, Jun 28–Jul 01, 2012, page 92 [131]

[97] Hilletofth, P; Lättilä, L. 2012. Agent based decision support in the supply chain context. Ind. Manage. Data Syst., vol. 112, Sep 8, page 1217 [66]

[98] Ghelichi, A; Abdelgawad, A. 2014. RFID Applications in Inventory Management Based on Kanban System. INTERNATIONAL CONFERENCE ON ELECTRICAL AND ELECTRONIC ENGINEERING (EEE 2014), APR 26–27, 2014, page 132 [57]

[99] Dias, JCQ; Calado, JMF; Osorio, AL; Morgado, LF. 2009. RFID together with multi-agent systems to control global value chains. Annu. Rev. Control, vol. 33, Dec, page 185 [33]

Chen e al. (2011) argue that a wide adoption of RFID across the supply chain will provide significant benefits. These include improved inventory accuracy and the increased visibility of stock. However, the valuation of these benefits remains challenging. “In a broader perspective, if we regard manufacturing as one node along the supply chain, then RFID also allows retailers to closely monitor the movement of their orders throughout their supply chains, from suppliers to freight forwarders, to ports and ocean carriers, and finally to distribution centres. Without this information, which corresponds to the situation where no RFID is used, the system may operate as if there is no information on the status of the production process”[100] (Chen et al, 2011).

1.4 Summary: Barriers to and drivers of ICT-enabled intelligent manufacturing

1.4.1 Innovation management

In general, managerial challenges in the implementation of advanced manufacturing technologies relate to top management support, organisational motivation and the extent of progress supervision and policy, structure and operating process compatibility. For example, difficulties may relate to managing the expectations of non-technologically driven management and with balancing the development of the strategic goals with pressures for commercial output. The optimization of organization processes rather than individual benefits poses challenging culture change management issues including operation strategy, organizational culture, organizational structure, implementation practices, and strategic consensus (Rangan et al, 2005). Also, it is claimed that there is an increased “gap between the competences needed by industry and those provided by the universities’ curricula”[101] (Secundo et al, 2013).

It can be difficult to demonstrate that an intelligent product environment can be deployed with industrial-scale information systems: specifying open, standard, user-friendly and widely-accepted interfaces, specifying what information is gathered, stored and distributed and how it is managed during the product’s lifecycle (McFarlane et al, 2013). Moreover, “traditional six-sigma techniques show strong limitations in highly changeable production contexts, characterized by small batch productions, customized, or even one-of-a-kind products”[102] (Ulewicz et al, 2014).

[100] Chen, LX; Chen, YH; Pang, Z. 2011. Dynamic Pricing and Inventory Control in a Make-to-Stock Queue With Information on the Production Status. IEEE Trans. Autom. Sci. Eng., vol. 8, Apr, page 361 [20]

[101] Secundo, G; Passiante, G; Romano, A; Moliterni, P. 2013. Developing the Next Generation of Engineers for Intelligent and Sustainable Manufacturing: A Case Study. Int. J. Eng. Educ, vol. 29, 1, page 248 [124]

[102] Ulewicz, S; Schutz, D; Vogel-Heuser, B. 2014. Integration of Distributed Hybrid Multi-Agent Systems into an Industrial IT Environment. 2014 12TH IEEE INTERNATIONAL CONFERENCE ON INDUSTRIAL INFORMATICS (INDIN), JUL 27–30, 2014, page 519 [142]

On the other hand, “the significance of intangible resources for business success has increased and may in some cases already be assessed as higher than the impact of tangible resources”[103] (Kohl et al, 2014). Hence, there is room for managerial ingenuity and innovation management. For example, when advanced manufacturing technologies are implemented successfully, they give a customer greater control over the processing of an order; allowing the customer to dynamically influence the way the order is produced, stored or transported (Fawcett et al, 2008).

In a multinational setting, it can be difficult to manage the challenges (and opportunities) of context, that is, the different nations’ political, regulatory, judicial, tax and labour environments (Isenberg, 2008). In addition, as drivers, nations may have tax policies supporting innovation, including incentives for R&D and tax benefits for ”advanced manufacturing” (Graetz and Doud, 2013).

Table 3. Barriers and drivers in ICT-enabled intelligent manufacturing, innovation management

	Barriers	Drivers
Environmental Context	• Difficulty in managing different nations’ political, regulatory, judicial, tax and labour environments	• Tax policies supporting innovation, for example, incentives for R&D, and tax benefits for ”advanced manufacturing”
Organizational Context	• Difficulties in managing the expectations of non-technologically driven management • Difficulties in balancing the development of the strategic goals with pressures for commercial output • Difficulty in managing collaborative workflows, increased inter-firm rivalry due to a misalignment of motives and behaviours among allying partners • Challenging culture change management issues, resistance to change • Challenges in decision execution: translating decisions into actions, both from a technical perspective and from the perspective of a compelling business model	• Significance of intangible resources for business success has increased and may in some cases already be assessed as higher than the impact of tangible resources
Technological Context	• Difficulty in demonstrating that an intelligent product environment can be deployed with industrial scale: specifying open, standard, user-friendly and widely-accepted interfaces, specifying what information is gathered, stored and distributed and how it is managed during the product’s lifecycle • Traditional six-sigma techniques show strong limitations in highly changeable	• Give a customer greater control over the processing of an order; allow the customer to dynamically influence the way the order is produced, stored or transported

[103] Kohl, H; Galeitzke, M; Steinhofel, E; Orth, R. 2014. Strategic Intellectual Capital Management as a Driver of Organisational Innovation. IFKAD 2014: 9th International Forum on Knowledge Asset Dynamics: Knowledge and Management Models for Sustainable Growth, Jun 11–13, 2014, page 1481 [78]

	production contexts, characterized by small batch productions, customized, or even one-of-a-kind products	

1.4.2 Advanced information systems

An important driver of the implementation of advanced information systems is the national culture and government/corporate policies. It can be difficult for the management to evaluate investments in information systems: benefits may be intangible and non-financial, and indirect project costs complicate the justification process further (Irani, 2002). One barrier to the implementation of an intelligent manufacturing system can be the “difficulty of analysing the real-time production performance for the shop-floor”[104] (Zhang et al, 2014).

On the other hand, ICT-enabled intelligent manufacturing is claimed to produce a number of financial benefits: reduced operating and admin costs, reduced stock levels, increased turnover, reduced IT operating costs and reduced quality costs. ICT-enabled intelligent manufacturing is expected to increase user friendliness of IS and adherence to best practice work patterns, organisational learning, and hence, also effectiveness of employees

Similarly, advanced information systems are expected to improve manufacturing operations in a number of ways: improve resource utilization, reduce manufacturing cycle times, reduce data processing time, increase inventory turns, improve accuracy and timeliness of information, enhance internal information sharing, reduce manufacturing lead times and increase integration of applications. These are claimed to lead to improved decision-making and improved vendor performance. ICT-enabled intelligent manufacturing allows the evaluation of various manufacturability aspects during the design stage and consequently a reduction in the costs and time to market of the designed products (Shukor and Axinte, 2009).

However, software alone cannot directly cause actions in the real world without connections to physical technologies such as actuators or transportation systems, or through interfaces to human operators (McFarlane et al, 2013). Companies “report difficulty in finding skilled labour, especially with industry-specific experience”[105] (Cormia et al, 2013). Unanticipated dynamic interactions due to repeated use or misuse of components makes it “increasingly difficult for plant personnel to anticipate, diagnose and control serious abnormal events in a timely manner”[106] and human operators tend to make erroneous decisions (Venkatasubramanian, 2005).

[104] Zhang, YF; Wang, WB; Liu, SC; Xie, GN. 2014. Real-Time Shop-Floor Production Performance Analysis Method for the Internet of Manufacturing Things. Adv. Mech. Eng., page 1, [158]

[105] Cormia, RD; Oye, MM; Nguyen, A; Skiver, D; Shi, M; Torres, Y. 2014. Integrating Electron Microscopy into Nanoscience and Materials Engineering Programs. SCANNING MICROSCOPIES 2014, SEP 16–18, 2014, page 92360N-1 [28]

[106] Venkatasubramanian, V. 2005. Prognostic and diagnostic monitoring of complex systems for product lifecycle management: Challenges and opportunities. Comput. Chem. Eng., vol. 29, May 15, page 1253 [1443]

Barriers may also occur because of the isolation of companies' IT systems; their communication, cooperation and integration may result in increasing overheads and quickly becomes unmanageable. Hence, the stability of operation of highly distributed systems must be considered (McFarlane et al, 2013).

Table 4. Barriers and drivers in ICT-enabled intelligent manufacturing, advanced information systems

	Barriers	Drivers
Environmental Context	• Difficulty in evaluating investments in information systems: intangible and non-financial benefits, together with indirect project costs that complicate the justification process • Difficulty in establishing performance metrics and making benefit-cost analysis • Challenges in vendor selection	• Supporting national culture and government/corporate policies, as being critical to advanced information systems implementation in multinational settings • Promises in enhanced company performance by improved decision-making, reduced operating and administrative costs, reduced stock levels, increased turnover, improved resource utilization, enhanced business processes and improved vendor performance • Promises in improved customer service by increased on-time shipments, improved quality, reduced quality costs, improved external information sharing and reduced service lead times
Organizational Context	• Optimizing organization processes rather than individual benefits poses challenging culture change management issues including operation strategy, organizational culture, structure, implementation practices and strategic consensus • Difficulty in finding skilled labour, especially with industry specific experience • Difficulty in developing innovative learning approaches and strategy to incentive the development of competence • Increasingly difficult for plant personnel to anticipate, diagnose and control serious abnormal events in a timely manner, human operators tend to make erroneous decisions	• Promises in enhanced productivity by adherence to best practice work patterns, enhanced internal information sharing, organisational learning and effectiveness of employees and roll out of a common vision
Technological Context	• Difficulty in analysing the real-time production performance for the shop-floor • Companies' IT systems are typically isolated and their communication, cooperation and in special cases also integration results in increasing overheads and quickly becomes unmanageable, the stability of operation of highly distributed systems must be considered	• Promises in enhanced productivity and efficiency by reduced manufacturing cycle times, reduced data processing time, increased inventory turns, improved accuracy and timeliness of information, reduced manufacturing lead times and increased integration of applications • Allow the evaluation of various manufacturability aspects during the design stage

1.4.3 Supply chain management

ICT-enabled intelligent manufacturing makes it possible to improve supply chain visibility, to conduct experiments and what-if analyses, and to improve the understanding of the real system. This improves communication within and between organizations in the supply chain. For example, physical product, information systems and financial flows can be closely aligned with each other throughout the supply chain incorporating the core company, its customers, suppliers and banks. The sharing of financial data as part of a cooperative strategy generated cost savings in areas such as foreign exchange and cash balances (Blackman et al, 2013).[107]

Another driver for ICT-enabled intelligent manufacturing is that it makes it possible to respond quickly and effectively to market demands. Close relationships with suppliers are claimed to leave room for special orders in unique times of high demand, helping satisfy the customer expectations (Fawcett et al, 2008).[108]

However, there are a number of barriers also. The barriers "include difficulty of accessing data from partners in the supply chain, difficulty of accessing data on a higher level of granularity and difficulty of retrieving data from other information systems"[109] (Hilletofth and Lattila, 2012). "Inter-firm rivalry" might even appear that follows a "misalignment of motives and behaviours among allying partners within the strategic supply chain"[110] (Fawcett et al, 2008).

In the arena of digital content delivery, difficulties are caused by the shift of power and change of roles within the supply chain. Also, it can be difficult to establish performance metrics and conduct benefit-cost analysis (Irani, 2002). For example, balancing the benefits of global sourcing strategies' cost-effectiveness against the limitations of off-shore productions can be a challenging task (Nath et al, 2008).

[107] Blackman, ID; Holland, CP; Westcott, T. 2013. Motorola's global financial supply chain strategy. Supply Chain Manag., vol. 18, 2, page 132 [6]
[108] Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, page 37 [53]
[109] Hilletofth, P; Lättilä, L. 2012. Agent based decision support in the supply chain context. Ind. Manage. Data Syst., vol. 112, Sep 8, page 1217 [66]
[110] Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, page 37 [53]

Table 5. Barriers and drivers in ICT-enabled manufacturing, supply chain management

	Barriers	Drivers
Environmental Context	• Expected shift of power and change of roles within the supply chain as it is digitalized • Difficulty in balancing the benefits of global sourcing strategies' cost-effectiveness against the limitations of off shore productions	• Revenue growth fuelled by increased responsiveness occurring at lower costs using fewer assets
Organizational Context	• Managerial complexity or misalignments in allying firms' processes and culture: information system and technological incompatibility, inadequate measurement systems, and conflicting organizational structures and culture	• Physical product, information systems and financial flows can be closely aligned with each other throughout the supply chain to improve supply chain visibility, to conduct experiments and what-if analyses, to improve the understanding of the real system and the possibility to improve communication
Technological Context	• Difficulty in accessing and retrieving data from partners and other information systems	• Improved ability to respond quickly and effectively to market demands; close relationships with suppliers leave room for special orders in unique times of high demand, helping satisfy customer expectations • Collaboration allows inventory to cycle through to customers faster: the two-fold result is increased revenues and decreased costs that can be shared across the chain

2 High performance manufacturing

2.1 Environmental context

2.1.1 Micro & nano manufacturing

Fundamental research on metals and metallic nanostructures (MMNs) promises to continue transforming metals science into innovative materials, devices, and systems. "The societal and economic impacts of metals and metallic nanostructures research will continue to be significant. They underlie systems and technologies critical to solving national and global grand challenges." [111] According to Handwerker and Pollock (2014), "innovations in metals, metal alloys, and metallic nanostructures are needed to advance systems in the following areas:

[111] Handwerker, CA; Pollock, TM. 2014. Emerging Science and Research Opportunities for Metals and Metallic Nanostructures. JOM, vol. 66, Jul, 2014, page 1321 [62]

- Energy generation, harvesting, and storage— thermoelectrics, batteries, fuel cells, advanced turbines, magnetic induction, motors, hydrogen production and storage, nuclear reactor materials, and separation membranes
- Propulsion and transportation—high-strength, high-performance, lightweight structures; materials designed for improved creep, impact, fatigue, or corrosion resistance; high-temperature metals, alloys, and coatings for extreme environments; non-destructive evaluation
- Electronics, telecommunication, and information technology—electronic packaging, process modelling, device nanostructures to overcome the end to Moore's law, thin film and nanostructured electrical interconnects, magnetic devices and motors, and sensors
- Sustainability—nanostructured metals for catalytic convertors, polymer catalysis, hydrogen and ammonia production, and low-pollution smelting and refining processes
- Health care—imaging systems; integrated in vivo sensors, electronics, and communication systems for health monitoring and drug delivery; prosthetics and implant materials and systems; and cancer treatment technologies
- Manufacturing—additive and nanomanufacturing technologies, nonequilibrium processing approaches, recycling and reuse, and rapid deployment of alternatives to "critical" materials"[112]

New performance gains in electronic computing require new materials. "In the short term, the silicon channel in transistors will be replaced by materials with higher mobility that are easier to "scale" (make thinner). In data storage, the goal is to have fast, non-volatile memory with a smaller cell size. In the long term, new architectures and new types of logic devices will be needed in order to further reduce power consumption. New materials cannot only boost performance, but can also add new functionalities, such as on-chip photonics, which can vastly improve interchip interconnects. The need for new materials is a big opportunity for materials research, but also a challenge. Replacement technologies must outperform conventional silicon technology, but also be compatible with the vast infrastructure of silicon manufacturing"[113] (Liu et al, 2014).

Micro-miniaturisation

Narayan (2012) reviews the transition of nanoscience to nanotechnology to manufacturing. His focus is on nanostructuring of materials for next-generation systems having superior performance. Narayan starts with the discussion of intrinsic advantages of nanoscale materials and systematic approach for transition into systems. "As the feature (grain) size of solid-state ma-

[112] Handwerker, CA; Pollock, TM. 2014. Emerging Science and Research Opportunities for Metals and Metallic Nanostructures. JOM, vol. 66, Jul, 2014, page 1321 [62]

[113] iu, CW; Ostling, M; Hannon, JB. 2014. New materials for post-Si computing. MRS Bull., vol. 39, Aau, page 658 [91]

terials decreases, the defect content reduces and below a critical size material can be defect-free. Since these critical sizes for most materials lie in 5–100 nm, there is a fundamental advantage and an unprecedented opportunity to realise the property of a perfect material. Along with this opportunity, there is a major challenge with respect to the large fraction of atoms at the interfaces, which must be engineered to realise the advantages of nanotechnology-based systems. The systems of interest are based upon strong novel structural materials, nanomagnetics for information storage, nanostructured or Nano Pocket LEDs, variety of smart structures based upon vanadium oxide and novel perovskites integrated with Si(100), and nanotechnology-based solutions to enhance fuel efficiency and reduce environmental pollution" (Narayan, 2012[114]).

According to Topham and Harrison (2008) the benefits of micro-miniaturisation go beyond simply smaller size and reductions in cost and the use of raw materials."[115] For example, in microelectronics, micro-scale structures lead to higher frequency operation and lower power consumption; in micro-mechanics, small feature size "structures have low mass and high resonant frequencies, enabling high sensitivity yet robust operation; and, in micro-fluidics, micro-channels exhibit highly laminar flow, providing the potential for chemistry at molecular scales and the ability to single out and manipulate individual living cells. These benefits are readily demonstrated in chip-scale components, but the integration of these components into macro-scale products is non-trivial, conventionally posing difficult questions and compromises in the domains of packaging, interconnection and design"[116] (Topham and Harrison, 2008).

Brice uses a modelling-assisted qualification approach for aerospace structural materials. "An example of how this approach might apply to the emerging field of additive manufacturing is discussed in detail. The development and implementation of new materials and manufacturing processes for aerospace application is often hindered by the high cost and long time span associated with qualification procedures. The data requirements necessary for material and process qualification are extensive and often require millions and multiple years to complete. Furthermore, this qualification data can become obsolete for even minor changes to the processing route. This burden is a serious impediment to the pursuit of revolutionary new materials and more affordable processing methods for air vehicle structures. The application of integrated computational materials engineering methods to this problem can help to reduce the barriers to rapid insertion of new materials and processes. By establishing predictive capability for the development of microstructural features in relation to processing and relating this to

[114] Narayan, J. 2012. Nanoscience to nanotechnology to manufacturing transition. Int. J. Nanotechnol., vol. 9, Dec 10, page 914 [102]

[115] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from integrated micro-features. ESTC 2008: 2nd Electronics System-Integration Technology Conference, vols 1 and 2, Proceedings, Sep 01–04, 2008, page 1311 [138]

[116] Ibidem.

critical property characteristics, a streamlined approach to qualification is possible"[117] (Brice, 2011).

2.1.2 Additive manufacturing

As mass production has migrated to developing countries, European and US companies are forced to rapidly switch to low volume production of more innovative, customised and sustainable products with high added value. To compete in this turbulent environment, manufacturers have sought new fabrication techniques for increased flexibility and for enabling economic low volume production. One such emerging technique is Additive Manufacturing (AM) (Lifton et al, 2014).

Additive manufacturing is expected to provide great advantages over traditional subtractive manufacturing. "One of the most important benefits is in cutting costs related to building parts due to a significant reduction in material waste. In addition, certain other manufacturing constraints are removed such as those related to the way in which the part is actually fabricated using a traditional process. This gives designers the opportunity to create their products in ways which were previously considered impossible to manufacture, for example, by defining the internal geometries of a component"[118] (Singh and Sewell, 2012).

Due to its diversification of materials, processes, system technology and applications, additive manufacturing has been synonymized with terminology such as Rapid Prototyping, 3D printing, free-form fabrication, Additive Layer Manufacturing, etc. (Ahuja et al, 2015). [119] Lifton, Lifton and Simon (2014) "investigate the options for additive rapid prototyping methods in microelectromechanical systems (MEMS) technology. Additive rapid prototyping technologies, such as stereolithography (SLA), fused deposition modelling (FDM) and selective laser sintering (SLS), all commonly known as three-dimensional (3D) printing methods, are reviewed and compared with the resolution requirements of the traditional MEMS fabrication methods."[120]

In the US, the Defence Advanced Research Projects Agency (DARPA) has a special interest in additive manufacturing. This interest "dates back to the mid-80s with seedling programmes that developed the foundational knowledge and equipment that led to the Solid Freeform Fabrication programme in 1990. The drivers for this program included reducing development times by enabling "tool-less" manufacturing as well as integration of design and fabrication

[117] Brice, CA. 2011. Unintended consequences: how qualification constrains innovation. Proceedings of the 1st World Congress on Integrated Computational Materials Engineering (ICME), JUL 10–14, 2011, page 241 [11]

[118] Singh and Sewell, 2012, page 619 [132]

[119] Ahuja, B; Karg, M; Schmidt, M. 2015. Additive Manufacturing in Production – Challenges and Opportunities. Laser 3D Manufacturing II, FEB 10–12, 2015, page 935304-1 [1]

[120] Lifton, VA; Lifton, G; Simon, S. 2014. Options for additive rapid prototyping methods (3D printing) in MEMS technology. Rapid Prototyping J., vol. 20, 5, page 403 [87]

tools. DARPA consistently pushed the boundaries of additive manufacture with follow-on programmes that expanded the material suite available for 3D printing as well as new processes that expanded the technology's capability base. Programs such as the Mesoscopic Integrated Conformal Electronics (MICE) programme incorporated functionality to the manufacturing processes through direct write of electronics. DARPA's investment in additive manufacture continues to this day, but the focus has changed. DARPA's early investments were focused on developing and demonstrating the technology's capabilities. Now that the technology has been demonstrated, there is serious interest in taking advantage of the attributes unique to the processing methodology (such as customization and new design possibilities) for producing production parts. Accordingly, today's investment at DARPA addresses the systematic barriers to implementation rather than the technology itself. The Open Manufacturing programme is enabling rapid qualification of new technologies for the manufacturing environment through the development of new modelling and informatics tools"[121] (Maher et al, 2014). Similarly, the Office of Naval Research manufacturing science programme "invested in basic R&D in AM since its beginnings. It continues to invest, currently focusing on developing cyber-enabled manufacturing systems for AM. It is believed that such computation, communication and control approaches will help in validating AM and moving it to the factory floor alongside CNC machines"[122] (Cooper, 2014).

Palanivel, Sidhar and Mishra (2015) argue that "aerospace and automotive industries provide the next big opportunities for additive manufacturing. Currently, the additive industry is confronted with four major challenges."[123] These challenges are presented in Figure 2 and relate to environment and energy, scale and cost of production and structural performance.

These challenges need to be addressed for the additive manufacturing technologies to be applied for new applications and create additional markets. "Specific potential success in the transportation sectors is dependent on the ability to manufacture complicated structures with high performance. Most of the techniques used for metal-based additive manufacturing are fusion-based because of their ability to fulfil the computer-aided design to component vision. Although these techniques aid in the fabrication of complex shapes, achieving high structural performance is a key problem due to the liquid-solid phase transformation" (Palanivel et al, 2015).

---

[121] Maher, M; Smith, A; Margiotta, J. 2014. A synopsis of the Defense Advanced Research Projects Agency (DARPA) investment in additive manufacture and what challenges remain. Laser 3D Manufacturing, Feb 05–06, 2014, page 897002-1 [94]

[122] Cooper, KP; Wachter, RF. 2014. Cyber-enabled manufacturing systems for additive manufacturing. Rapid Prototyping J., vol. 20, 5, page 897003 [26]

[123] Palanivel, S; Sidhar, H; Mishra, RS. 2015. Friction Stir Additive Manufacturing: Route to High Structural Performance. JOM, vol. 67, Mar, page 616 [108]

According to Dawes, Bowerman and Trepleton (2015), the supply chain for metal powders used in additive manufacturing is currently experiencing exponential growth. “With this growth come new powder suppliers, new powder manufacturing methods and increased competition. The high number of potential supply chain options provides AM service providers with a significant challenge when making decisions on powder procurement.”[124] Dawes, Bowerman and Trepleton (2015) provide “an overview of the metal powder supply chain for the AM market and aims to give AM service providers the information necessary to make informed decisions when procuring metal powders. The procurement options are categorised into three main groups, namely: procuring powders from AM equipment suppliers, procuring powders from third party suppliers and procuring powders directly from powder atomisers. Each of the procurement options has its own unique advantages and disadvantages. The relative importance of these will depend on what the AM equipment is being used for, for example research, rapid prototyping or producisation. The future of the metal AM powder market is also discussed.”[125]

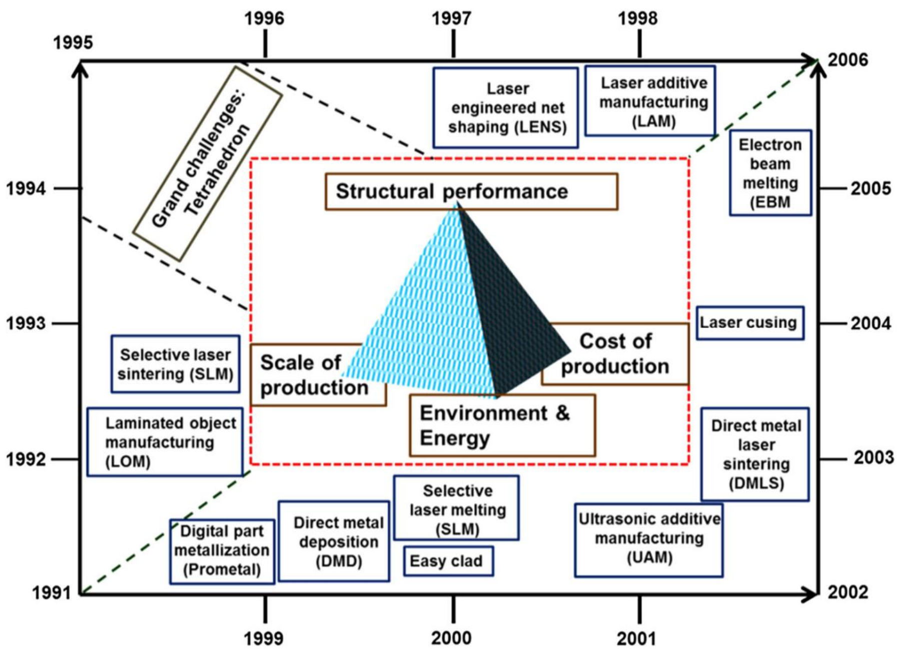


Figure 2. Chronological sequence showing the development of metal-based additive technologies. The grand challenge tetrahedron showing the obstacles faced by the metal-based AM community is inscribed (source: Palanivel et al. 2015[126])

[124] Dawes, J; Bowerman, R; Trepleton, R. 2015. Introduction to the Additive Manufacturing Powder Metallurgy Supply Chain Exploring the production and supply of metal powders for AM processes. Johns. Matthey Technol. Rev., vol. 59, Jul, page 243 [32]

[125] Ibidem.

[126] Palanivel, S; Sidhar, H; Mishra, RS. 2015. Friction Stir Additive Manufacturing: Route to High Structural Performance. JOM, vol. 67, Mar, page 617 [108]

2.1.3 Advanced machinery

Robot selection

Selection of a robot for a specific industrial application is one of the most challenging problems in real time manufacturing. Moreover, this problematic has become increasingly complicated due to increase in complexity, advanced features and facilities that manufacturers are continuously incorporating into the robots. "At present, different types of industrial robots with diverse capabilities, features, facilities and specifications are available in the market. Manufacturing environment, product design, production system and cost involved are some of the most influencing factors that directly affect the robot selection decision"[127] (Chatterjee et al, 2010). For example, "the oil and gas context presents a challenging work environment for robots, as they are exposed to variable and often extreme weather and need to be safe for use alongside explosive hydrocarbons"[128] (Heyer, 2010). The decision maker needs to identify and select the best suited robot in order to achieve the desired output with minimum cost and specific application ability (Chatterjee et al, 2010).[129] "The production system, comprising a variety of applications with different specifications and demands, perceives the necessity for rapid and effective decisions. In addition, the procedure of robot selection is encumbered by the number of alternative options and the nature of their characteristics"[130] (Koulouriotis and Ketipi, 2014).

For small and medium-sized enterprises (SMEs), there are two critical challenges in adopting industrial robots. These are "flexibility and cost, as the number of tasks of the same type can be limited because of the size of an SME. The challenges can be alleviated by redesigning, reusing, remanufacturing, recovering, recycling and reducing (6R). The 6R processes allow a robot to adopt new tasks, increase its utilization rate and reduce unit costs of products"[131] (Bi et al, 2015).

---

[127] Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, Oct, page 483 [18]

[128] Heyer, C. 2010. Human-Robot Interaction and Future Industrial Robotics Applications. IEEE/RSJ 2010 International Conference on Intelligent Robots and Systems (IROS 2010), Oct 18–22, 2010, page 4749 [65]

[129] Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, Oct, page 483 [18]

[130] Koulouriotis, DE; Ketipi, MK. 2014. Robot evaluation and selection Part A: an integrated review and annotated taxonomy. Int. J. Adv. Manuf. Technol., vol. 71, Mar, page 1371 [80]

[131] Bi, ZM; Liu, YF; Baumgartner, B; Culver, E; Sorokin, JN; Peters, A; Cox, B; Hunnicutt, J; Yurek, J; O'Shaughnessey, S. 2015. Reusing industrial robots to achieve sustainability in small and medium-sized enterprises (SMEs). Ind. Robot, vol. 42, 3, page 264 [5]

Human–robot interaction

According to Das, identifying and solving of specific ergonomic problems is a prerequisite for obtaining maximum benefit from the implementation of industrial robots. These problems include "socio-psychological factors, systems safety design, communications, training, and workplace design. For the successful implementation of industrial robots, management should take timely action with regard to advanced planning procedures, user involvement plans, communication channels, company labour policies, and continuous training programmes" [132] (Das, 2001).

In robotics research, much attention is devoted for how to manipulate industrial robots that interact with human operators. This interest stems from the perception that "the integration of human operators into robot-based manufacturing systems may increase productivity by combining the abilities of machines with those of humans. In such a Human–Robot–Interaction (HRI) setting, the challenge is to manipulate the robots both safely and efficiently"[133] (Ding et al, 2011).

2.2 Organizational Context

2.2.1 Micro & nano manufacturing

Recently, people have started to integrate micro-capabilities directly into macro products. This means "leaving behind the comfort of component-level hierarchical design and manufacture, and adopting a holistic approach to both. According to this approach, electronics cannot simply reside within the confines of chips cut from wafers, mechanics cannot be limited by MEMS production processes rooted in the flat-land of silicon, and micro-fluidic applications need to scale seamlessly from picolitres per hour to millilitres per second, or more"[134] (Topham and Harrison, 2008). "Whilst radical manufacturing process innovation is tackling the details of micro-capability integration through projects such as 3D-Mintegration, there are formidable challenges in the conception and design of whole products and systems that can benefit from the approach"[59]. Topham and Harrison (2008) "discuss the challenges faced by designers in this developing domain, introduces the idea of conceptual transforms from 2D-map to 3D-space and suggests directions for further work." [59]

[132] Das, B. 2001. Ergonomics considerations and management action in the implementation of industrial robots. Hum. Factors Ergon. Manuf., vol. 11, SUM, page 269 [31]

[133] Ding, H; Wijaya, K; Reissig, G; Stursberg, O. 2011. Optimizing Motion of Robotic Manipulators in Interaction with Human Operators. Intelligent Robotics and Applications, PT I: ICIRA 2011, Dec 06–08, 2011, page 520 [34]

[134] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from integrated micro-features. ESTC 2008: 2nd Electronics System-Integration Technology Conference, vols 1 and 2, Proceedings, Sep 01–04, 2008, page 1311 [138]

Espig et al. (2012) report on "the development of a process workflow and, the setup of a pilot manufacturing line, taking into account the requirements to adapt the energy content, the size and the shape to the powered product."[135] Espig et al. (2012) "map the advantages of an automated production process and cover the introduction of process documentation, aspects of quality control, cost minimization and the efficiency improvement. A basic concept for an adapted digital workflow comprising the definition of relevant metadata and job ticket content, which is required for further industrial fabrication of thin film batteries"[136], is presented.

2.2.2 Additive manufacturing

Specialized products often require the development of new processes and production facilities. These can be very capital intensive. Laser-based additive manufacturing has shown "the potential to reduce the development costs and has eliminated the complexity factor. As a result, it becomes possible to manufacture structures of complex shapes and sizes. Efforts are still ongoing for developing a cost effective solution to additive manufacturing of non-metals and metals"[137] (Angrish, 2014).

Lindemann et al. (2015) "present a methodology to help end-users to find appropriate part candidates for the use of the additive manufacturing technology."[138] These will "be capable of bringing AM into their businesses. The concept furthermore includes approaches for redesigning current available parts and helps to estimate the economic implications of the use of the technology. The approach starts to discuss general economic aspects for the successful use of AM. While describing the introduction of new technologies into existing businesses, the importance of an appropriate part selection for AM is pointed out. A methodology for a part selection process is presented, and the different criteria are developed. The methodology for the redesign process helps to identify the main functions of the products targeted and the relevant environment, so one can benefit from the various advantages that AM has to offer. The selection methodology helps to ask the right questions and to reduce the effort."[139]

"There is great skill required in making effective use of AM technology, and given the wide range of systems and processes available, expert knowledge is often in short supply. Without this knowledge, attempts to use AM often result in disappointment for the end user, as the

---

135 Espig, M; Siegel, F; Hammerschmidt, J; Willert, A; Baumann, RR. 2012. Central Challenges When up Scaling the Manufacturing of Thin-Film Battery Applications. NIP28: 28th International Conference on Digital Printing Technologies / Digital Fabrication 2012, Sep 09–13, 2012, page 168 [40]

136 Ibidem.

137 Angrish, A. 2014. A Critical Analysis of Additive Manufacturing Technologies for Aerospace Applications. 2014 IEEE Aerospace Conference, Mar 01–08, 2014, page 1 [2]

138 Lindemann, C; Reiher, T; Jahnke, U; Koch, R. 2015. Towards a sustainable and economic selection of part candidates for additive manufacturing. Rapid Prototyping J., vol. 21, 2, page 216 [89]

139 Ibidem

products may fail to deliver what is expected in terms of form, fit or function"[140] (Singh and Sewell, 2012). For example, Ng, Chua and Leong investigate how designers exploit the full potential of additive manufacturing. AM yields a broad range of advantageous properties including the possibility to fabricate mechanical multi-body structures. Jansen et al. (2014) discuss the design process and considerations involved and attempt to distil design guidelines. "The result is a functioning walking mechanism of 74 components can be fabricated at once without human intervention. Part consolidation by AM could bring great benefits in future product design applications. The findings show that complex multi-body mechanical structures with more than 70 elements are feasible by AM without assembly. This presents new business opportunities for AM service bureaus and novel product opportunities for designers"[141] (Jansen et al, 2014). Moreover, Singh and Sewell (2012) describe the creation of an easy-to-use tool which enables a wide range of users to access and assess the strengths and weaknesses of AM process for manufacturing products.[142]

Ng et al. "discuss some of the challenges encountered in teaching AM and presents the use of multimedia learning aids as potential solutions to the challenges. The software designed to complement the book 3D Printing and Additive Manufacturing: Principles and Applications is presented as a case study for the use of multimedia in teaching AM. Some suggestions to further improve students' AM learning experience were also discussed briefly"[143] (Ng et al, 2014).

2.2.3 Advanced machinery

Cloud Manufacturing

Cloud computing is bringing new service models and research opportunities in the manufacturing and service industries. It promises advantages such as ubiquitous accessibility, convenient scalability and mobility. Combining the emerging industrial big data technology and the implementation of sensor networks, cloud computing can become a hosting platform for autonomous data mining and cognitive learning algorithms. For machine health monitoring and prognostics, Yang et al. (2015) investigate "the challenges imposed by industrial big data such as heterogeneous data format and complex machine working conditions and further propose a systematically designed framework as a guideline for implementing cloud-based machine

[140] Singh, B; Sewell, N. 2012. Knowledge based process planning and design for Additive Manufacturing (KARMA). Innovative developments on virtual and physical prototyping, Sep 28–OCT 01, 2011, page 619 [132]

[141] Jansen, B; Doubrovski, EL; Verlinden, JC. 2014. Animaris Geneticus Parvus Design of a complex multi-body walking mechanism. Rapid Prototyping J., vol. 20, 4, page 311 [72]

[142] Singh, B; Sewell, N. 2012. Knowledge based process planning and design for Additive Manufacturing (KARMA). Innovative developments on virtual and physical prototyping, Sep 28–OCT 01, 2011, page 619 [132]

[143] Ng, CH; Chua, CK; Leong, KF. 2014. Teaching of additive manufacturing technology – A case study in the use of multimedia learning aids. High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping, Oct 01–05, 2013, page 565 [105]

health prognostics. Specifically, so as to ensure the effectiveness and adaptability of the cloud platform for machines under complex working conditions, two key design methodologies are presented which include the standardized feature extraction scheme and an adaptive prognostics algorithm."[144]

Similarly, a focal problem with maintenance as well as support of industrial robotics is the need to manage the ever-increasing information flow and system complexity of production cells that incorporate equipment from different producers"[145] (Chioreanu et al, 2013). Hoshino et al. (2010) study a batch manufacturing system with multiple industrial robots. In this kind of manufacturing system, there are two primary challenges: bottleneck prevention and restraint. To resolve them, suitable operational techniques with respect to the material-handling and material-processing robots (MHR and MPR) are needed in order for them to operate appropriately while relating to each other.[146] Similarly, "an industrial part may need to be partitioned into multiple patches because of its complexity. The trajectories of all patches must be connected to form a complete trajectory for the industrial part in order to minimize the material waste and process cycle time."[147] "Generating a robot tool trajectory to manufacture an automotive part to satisfy material distribution requirements is still very challenging due to the complexity of the problems"[148] (Chen and Xi, 2012).

When managing advanced information systems, people continuously try to improve uptime and simultaneously reduce the amount of direct supervision required for operations. However, when there is randomness in system components, this can be difficult to attain. For example, "when automating metal cutting operations, the randomness of tool life requires ensuring that there are sufficient cutting tools available on the machines to meet unsupervised production requirements, and variations in tool life can make planning challenging."[149] Noel, Sodhi and Lamond (2007) focus "on the problem of selecting the cutting speeds for processing a set of part types by an unsupervised metal cutting flexible machine in such a situation."[150]

---

[144] Yang, SH; Bagheri, B; Kao, HA; Lee, J. 2015. A Unified Framework and Platform for Designing of Cloud-Based Machine Health Monitoring and Manufacturing Systems. J. Manuf. Sci. Eng.-Trans. ASME, vol. 137, Aug, page 040914-1 [153]

[145] Chioreanu, A; Brad, S; Brad, E. 2013. Knowledge Modelling of E-maintenance in Industrial Robotics. Interdisciplinary research in engineering: steps towards breakthrough innovation for sustainable development, feb 25–mar 01, 2013, page 603 [22]

[146] Hoshino, S; Seki, H; Naka, Y; Ota, J. 2010. Multirobot Coordination for Flexible Batch Manufacturing Systems Experiencing Bottlenecks. IEEE Trans. Autom. Sci. Eng., vol. 7, Oct, page 887 [67]

[147] Chen, HP; Xi, N. 2012. Automated Robot Tool Trajectory Connection for Spray Forming Process. J. Manuf. Sci. Eng.-Trans. ASME, vol. 134, Apr, page 021017-1 [19]

[148] Ibidem.

[149] Noel, M; Sodhi, MS; Lamond, BF. 2007. Tool planning for a lights-out machining system. J. Manuf. Syst., vol. 26, Apr 3, page 161 [107]

[150] Noel, M; Sodhi, MS; Lamond, BF. 2007. Tool planning for a lights-out machining system. J. Manuf. Syst., vol. 26, Apr 3, page 161 [107]

Robots in dynamic environments

Typically, industrial robots operate in relatively static environments and in large numbers. They have been designed for performing operations quickly, repeatedly and accurately. "New developments in regions difficult or dangerous for humans to work in could be enabled with maintenance, inspection and repairs carried out by remotely-controlled industrial robots. This new application area highlights some difficulties with today's robots, as they do not adapt well to dynamic environments, do not offer rich human-robot interaction and are not simple for end-users to program"[151] (Heyer, 2010).

Heyer says that "as robots are introduced, issues of trust and accountability come to the fore, as well as how they fit into organisational structures. If robots have too little autonomy, human operators will waste time attending to robots instead of attending to their work tasks. If robots are highly autonomous, situational awareness of plant activity is diminished. A balance needs to be struck to find a level of autonomy suitable for the task, the realistic capabilities of the automation, and the need to actively engage human operators in a constructive fashion. These issues also relate to what form the interface takes for remote or the co-located robot control, as well as how information and activity is represented for remote operators"[152] (Heyer, 2010).

According to Neto (2013), "manufacturing system designers are looking for more intuitive ways to program robots, especially using the CAD drawings of the production system they developed."[153] The author "presents an industrial application of a novel CAD-based off-line robot programming (OLP) and simulation system in which the CAD package used for cell design is also used for OLP and robot simulation. Thus, OLP becomes more accessible to anyone with a basic knowledge of CAD and robotics. The system was tested in a robot-assisted sheet metal bending cell."[154]

Brogardh (2007) suggests that "lightweight robot concepts could be used on future car manufacturing and impact future automation of small and medium-sized enterprises (SMEs). Such a development could result in modular robots and in control schemes using sensors in the robot arm structure, sensors that could also be used for the implementation of redundant safe control. Introducing highly modular robots will increase the need of robot installation support, making Plug and Play functionality even more important. One possibility to obtain a highly

---

[151] Heyer, C. 2010. Human-Robot Interaction and Future Industrial Robotics Applications. IEEE/RSJ 2010 International Conference on Intelligent Robots and Systems (IROS 2010), OCT 18–22, 2010, page 4749 [65]

[152] Ibidem.

[153] Neto, P. 2013. Off-line Programming and Simulation from CAD Drawings: Robot-Assisted Sheet Metal Bending. 39th Annual Conference of the Ieee Industrial Electronics Society (IECON 2013), Nov 10–14, 2013, page 4233 [104]

[154] Ibidem.

modular robot programme could be to use a recently developed new type of parallel kinematic robot structure with large work space in relation to the robot foot print. For further efficient use of robots,"[155] Brogardh (2007) introduces a "scenario of adaptive robot performance. This means that the robot control is optimised with respect to the thermal and fatigue load on the robot for the specific programme that the robot performs."[156]

2.3 Technological Context

2.3.1 Micro & nano manufacturing

Microelectronics packaging

According to Bechtold (2009), ceramic packaging solutions are more reliable than organic technologies and require only a fraction of the development cost of monolithic semiconductors. "System in package integration capabilities, thermal management, temperature resistivity and heterogeneous system integration (matching different Thermal Coefficient of Expansions, TCEs) are the driving forces for the utilisation of ceramic substrate technologies in microelectronics"[157] (Bechtold, 2009).

Research by Bechtold (2009) "gives a wide and comprehensive overview of today's ceramic substrate technologies used in microelectronic packaging."[158] "LTCC material systems, widely used in the automotive and the telecommunication business, will be highlighted, and some market penetrating applications as well as low volume applications in the field of sensors will be presented to demonstrate the advantages of ceramic multilayer substrates."[159] Bechtold demonstrates the perspectives and challenges for ceramic substrates as enabler from the technical point of view in Table 6.

---

[155] Brogardh, T. 2007. Present and future robot control development – An industrial perspective. Annu. Rev. Control, vol. 31, 1, page 69 [12]

[156] Ibidem.

[157] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Technologies. 2009 European Microelectronics and Packaging Conference (Empc 2009), vols 1 and 2, Jun 16–18, 2009, page 798 [4]

[158] Ibidem.

[159] Ibidem.

Table 6. Future market needs, technical trends and actual developments in current R&D programmes (source: Bechtold, 2009)[160]

Opportunity	Challenge	Technical Requirements
Biotechnology, chemical sensors	Lab on Chip, integrated fluidic, integrated reactors and sensors	Chemical performance, biocompatibility, fluidic interfaces
Heterogeneous Integration	High pin count, quad flat package (QFP), land grid array (LGA), ball grid array (BGA)	Flatness, TCE matching of Ceramic to PCB
System in Package	3D interconnection, passive integration, thermal management	New and adapted materials, new and adapted processes
MEMS Packaging	3D integration, hermeticity, Wafer level packaging	TCE matching of ceramic to Si, no XY shrinkage
MOEMS Packaging	Integration of optical and electrical conductors	no XY shrinkage, excellent planarity and accuracy
Energy efficiency	High power/high complexity integration	High currency conductor, micro cooler, high temp.

Bechtold (2009) argue "that standard ceramic substrates for thick film and thin film integration are at their limits and that no significant R&D efforts are envisaged. Complexity, temperature and power are permanently increasing and will drive the future developments of the technology with respect to cost and performance."[161]

The complexity of microsystems and sensors is constantly increasing and requires new packaging solutions. "The major R&D efforts will be put into innovative LTCC technology to cope with the increasing complexity of microelectronic and microsystem devices and into direct bonded copper (DBC) and comparable technologies to cope with increasing power and operating temperatures requirements. The R&D roadmaps for LTCC ceramic are dominated by efforts for cost improvements at process level such as self-constrained sintering, high resolution screen printing, micro via laser drilling, wafer level packaging, for cost improvements at integration level with new functional materials like high k, low k, high permeability and TCE graduation

[160] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Technologies. 2009 European Microelectronics and Packaging Conference (Empc 2009), vols 1 and 2, Jun 16–18, 2009, page 808 [4]

[161] Ibidem.

and cost improvements by combining and optimising different technologies for specific applications"[162] (Bechtold, 2009).

Filler particles

Polymer materials, typically epoxy resins, are widely used in microelectronics packaging. Polymer materials "are established in printed circuit board manufacturing, for adhesives as die attach glues or for encapsulants as moulding compounds, glob tops or underfill materials. Low cost and mass production capabilities are the main advantages of these materials. But, like all polymers they cannot provide a hermetical sealing due to their permeability properties"[163] (Braun et al, 2008). Humidity resistance "is gaining increased importance when considering the trend towards System in Package, where a multitude of components is encapsulated to form one SiP that incorporates a large number of different material interfaces and interconnects. All these interfaces and interconnects need to be protected from degradation caused by moisture ingress, without allowing much increased package volume or package cost"[164] (Braun et al, 2008).

Braun explains that "the susceptibility to water diffusion through the polymer and along the interfaces is a drawback for polymer materials in general. Water inside a microelectronic package might lead to softening of the material and to a decreasing adhesive strength and resulting delaminations close to solder bumps or wire bonds reducing package reliability by decreasing the package structural integrity. During package reflow, the incorporated humidity might lead to popcorning, i.e. abrupt evaporation of humidity during reflow soldering, which is one major problem during plastic package assembly. The introduction of high temperature lead-free soldering processes has even increased this issue. Therefore, plastic packaging materials with enhanced humidity resistance would increase package reliability during assembly and lifetime without cost increase and with no changes in processing"[165] (Braun et al, 2008). For example, "medical applications need to provide biocompatibility, highest miniaturization, rough treatment, autoclave sterilization and harsh environment e. g. humidity, wax, dust, blood or urine to be applicable. And microelectronics packaging needs to protect the functional elements of the microsystem against these rigid conditions. And, with a different set of media, packaging needs to fulfil the same task for automotive applications, where a growing number of control units and sensor systems under the hood in the transmission oil or petrol can be found. For

[162] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Technologies. 2009 European Microelectronics and Packaging Conference (Empc 2009), vols 1 and 2, Jun 16–18, 2009, page 808 [4]

[163] Braun, T; Hausel, F; Bauer, J; Wittler, O; Mrossko, R; Bouazza, M; Becker, KF; Oestermann, U; Koch, M; Bader, V; Minge, C; Aschenbrenner, R; Reichl, H. 2008. Nano-particle enhanced encapsulants for improved humidity resistance. 58th Electronic Components & Technology Conference, Proceedings, 2008, page 198 [10]

[164] Ibidem.

[165] Ibidem.

both markets low cost packaging concepts with high media resistivity is needed" [166](Braun et al, 2012).

According to Braun et al. (2012) "there are a lot of nano- and micro-sized filler particles with the potential to enhance the humidity barrier properties of encapsulants. Working principles of these particles may range from large surface impact of nano-particles, barrier functionality due to stacked layer formation (nano-clays), highly hydrophobic particle surface and molecular water catcher function"[167] (Braun et al, 2012). Braun et al. (2008) describe "the potential of different nano-particles as additives for plastic packaging materials for enhanced humidity resistance/barrier enhancement within microelectronic packages."[168] "From the large variety of fillers available this work mainly focuses on three different types: nano-sized silica, modified bentonite and zeolites."[169]

Among other applications, carbon nanoparticles "may have a critical impact in loss-free, more compact and efficient thermal storage systems, as well as thermally conducting polymeric materials for innovative low-cost heat exchangers."[170] In this respect, Fasano et al. (2015) "both review and numerically investigate the impact that nanotechnology (and in particular carbon-based nanostructures) may have in the near future"[171] (Fasano et al, 2015). Indeed, "the past two decades have witnessed the emergence and rapid growth of the research field of nanoscale thermal transport. Much of the work in this field has been fundamental studies that have explored the mechanisms of heat transport in nanoscale films, wires, particles, interfaces, and channels. However, in recent years there has been an increasing emphasis on utilizing the fundamental knowledge gained toward understanding and improving device and system performances."[172] Shi et al. (2015) attempt "to provide an evaluation of the existing and potential impacts of the basic research efforts in this field on the developments of the heat transfer discipline, workforce, and a number of technologies, including heat-assisted magnetic record-

---

166 Braun, T; Bauer, J; Georgi, L; Becker, KF; Koch, M; Aschenbrenner, R; Lang, KD. 2012. Enhancement of Barrier Properties of Encapsulants for Harsh Environment Applications. 2012 IEEE 62nd Electronic Components And Technology Conference (ECTC), May 29–JUN 01, 2012, page 1418 [9]

167 Braun, T; Bauer, J; Georgi, L; Becker, KF; Koch, M; Aschenbrenner, R; Lang, KD. 2012. Enhancement of Barrier Properties of Encapsulants for Harsh Environment Applications. 2012 IEEE 62nd Electronic Components And Technology Conference (ECTC), May 29–JUN 01, 2012, page 1418 [9]

168 Braun, T; Hausel, F; Bauer, J; Wittler, O; Mrossko, R; Bouazza, M; Becker, KF; Oestermann, U; Koch, M; Bader, V; Minge, C; Aschenbrenner, R; Reichl, H. 2008. Nano-particle enhanced encapsulants for improved humidity resistance. 58th Electronic Components & Technology Conference, Proceedings, 2008, page 198 [10]

169 Ibidem.

170 Fasano, M; Bigdeli, MB; Sereshk, MRV; Chiavazzo, E; Asinari, P. 2015. Thermal transmittance of carbon nanotube networks: Guidelines for novel thermal storage systems and polymeric material of thermal interest. Renew. Sust. Energ. Rev., vol. 41, Jan, page 1028 [52]

171 Ibidem.

172 Shi, L; Dames, C; Lukes, JR; Reddy, P; Duda, J; Cahill, DG; Lee, J; Marconnet, A; Goodson, KE; Bahk, JH; Shakouri, A; Prasher, RS; Felts, J; King, WP; Han, B; Bischof, JC. 2015. Evaluating Broader Impacts of Nanoscale Thermal Transport Research. Nanoscale Microscale Thermophys. Eng., vol. 19, Apr 3, page 127 [126]

ing, phase change memories, thermal management of microelectronics, thermoelectric energy conversion, thermal energy storage, building and vehicle heating and cooling, manufacturing, and biomedical devices. The goal is to identify successful examples, significant challenges and potential opportunities where thermal science research in nanoscale has been or will be a game changer."[173]

Large-area, organic and printed electronics seems a promising way to develop various applications of functional devices. For most of the applications, "a reliable supply of electric energy tailored with respect to functional devices and applications is a mandatory, making thin-film battery a challenging area of research. Among a variety of manufacturing concepts, printing technologies and their established workflow provide interesting opportunities to fully integrate the battery in a product by customizing its size and shape regarding the device to be driven by that battery. Hence, these printed electronics applications will contribute a new momentum in the packaging market"[174] (Espig et al, 2012).

Precision machining

Optics and micro-electronics science and technology are advancing quite rapidly at the moment. These new advances and requirements bring challenges and opportunities to ultra-precision machining technology., Indeed, ultra-precision machining technology "has become the core technology of the manufacture and represent the highest level of fabrication domain. To meet the new requirement of ultra-precision and ultra-smooth and miniaturization, ultra-precision machining technology using micro machine tool is becoming a good choice to fabricate ultra-precision microstructure surface because of the advantage of low cost, high efficiency and flexibility"[175] (Zhang et al, 2010). In a similar vein, Liaw and Shirinzadeh (2010) "present a robust methodology for constrained motion-tracking control of piezo-actuated flexure-based four-bar micro/nano manipulation mechanisms."[176] "An advanced control methodology is formulated for achieving high-precision motion tracking in the field of micro/nano manipulation. In particular, the established control methodology is useful for accomplishing difficult tasks that require the tracking of specified motion trajectories in a constrained environment having

[173] Shi, L; Dames, C; Lukes, JR; Reddy, P; Duda, J; Cahill, DG; Lee, J; Marconnet, A; Goodson, KE; Bahk, JH; Shakouri, A; Prasher, RS; Felts, J; King, WP; Han, B; Bischof, JC. 2015. Evaluating Broader Impacts of Nanoscale Thermal Transport Research. Nanoscale Microscale Thermophys. Eng., vol. 19, Apr 3, page 128 [126]

[174] Espig, M; Siegel, F; Hammerschmidt, J; Willert, A; Baumann, RR. 2012. Central Challenges When up Scaling the Manufacturing of Thin-Film Battery Applications. NIP28: 28th International Conference on Digital Printing Technologies / Digital Fabrication 2012, Sep 09–13, 2012, page 168 [40]

[175] Zhang, P; Wang, B; Liang, YC. 2010. Fabrication of microstructure array by means of ultra-precision micro-milling. 5th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Advanced Optical Manufacturing Technologies, Apr 26–29, 2010, page 76550U-1 [156]

[176] Liaw, HC; Shirinzadeh, B. 2010. Constrained Motion Tracking Control of Piezo-Actuated Flexure-Based Four-Bar Mechanisms for Micro/Nano Manipulation. IEEE Trans. Autom. Sci. Eng., vol. 7, Jul, page 699 [86]

a certain degree of unknown stiffness. This control methodology will greatly benefit many advanced areas, which include micro-manufacturing, microassembly, microsurgery, biotechnology, and nanotechnology."[177]

In order to deal with part variations and system uncertainties, the process parameters of high precision robotic assembly have to be tuned accordingly. "Some methods such as design-of-experiment, artificial neural network and genetic algorithms have been proposed to optimize these parameters offline. However, these parameters have to be retuned for different batches due to part variations, which increases the production cost and reduces the manufacturing efficiency."[178] "Because of the complexity of high precision assembly process, it is challenging to build a physical model in order to establish the relationship between an assembly process and its process parameters"[179] (Li et al, 2014).

As the micro products industries are establishing to meet high level of demand, non-contact metrology systems are gaining popularity. "So far, the production technologies are well advancing in the form of lithography and non-lithography-based techniques. But, the dimensional inspection at micro-meso scale is not possible with conventional touch based systems. Micro-meso (10 mu m to few mm) scale artefact inspection needs non-conventional methods as compared to the well-established contact methods for normal large size manufacturing. The inspection of these parts is a challenge for the micro-manufacturing industry. Non-contact metrology inspection has turned out to be a solution to this problem" [180] (Wahab et al, 2014).

Non-destructive Evaluation (NDE) "seeks to provide an adequate science base for NDT to become a quantitative science. It was seen to be necessary to better detect, size and type defects, improve the reliability of inspection, and probability of detection (POD). There is particular interest in estimating the potential defects could have on performance or potential for loss of structural integrity, under various loading or stressor conditions, and ultimately implement risk-based reliability assessments. NDE must be seen more as a part of the wide field of engineering, as an interdisciplinary endeavour, that brings together the expertise of materials science and metrology, together with the underlying physics for inspection methods, as well as statistics, computers, robotics and software. The adoption of advanced manufacturing, will require new metrology tools and methods to provide data for assessing new materials includ-

---

[177] Liaw, HC; Shirinzadeh, B. 2010. Constrained Motion Tracking Control of Piezo-Actuated Flexure-Based Four-Bar Mechanisms for Micro/Nano Manipulation. IEEE Trans. Autom. Sci. Eng., vol. 7, Jul, page 699 [86]

[178] Li, BB; Chen, HP; Jin, TD. 2014. Industrial Robotic Assembly Process Modeling Using Support Vector Regression. 2014 IEEE/RSJ International Conference On Intelligent Robots And Systems (Iros 2014), Sep 14–18, 2014, page 4334 [84]

[179] Ibidem.

[180] Wahab, A; Khalid, A; Nawaz, R. 2014. Non-Contact Metrology Inspection System for Precision Micro Products. 2014 International Conference on Robotics and Emerging Allied Technologies in Engineering (ICREATE), Apr 22–24, 2014, page 151 [146]

ing powder metals, as used in additive manufacturing, and various composites"[181] (Bond, 2014). Bond (2015) discusses the "needs and opportunities for NDE to provide reliable, effective and economic inspection and monitoring for energy systems. It introduces issues of materials, defects and allowables, the evolution of advanced NDT and NDE and then considers examples of NDE for energy systems. These include applications in the petrochemical industry, advanced and additive manufacturing, solar cells, wind turbines, nuclear systems and some underlying issues of large scale composites, pipes and concrete."[182]

Thin films

Plasma-assisted atomic layer deposition (ALD) is an energy-enhanced method for the synthesis of ultra-thin films. The use of plasma gives more freedom in processing conditions and in the use of different material properties compared with the conventional ALD method. "Due to the continuous miniaturization in the microelectronics industry and the increasing relevance of ultra-thin films in many other applications, the deposition method has rapidly gained popularity in recent years, as is apparent from the increased number of articles published on the topic and of plasma-assisted ALD reactors installed"[183] (Profijt et al, 2011). Profijt et al. (2011) present the benefits and challenges provided by the use of a plasma step and show that "the use of a plasma leads to a wider choice in material properties, substrate temperature, choice of precursors, and processing conditions, but that the processing can also be compromised by reduced film conformality and plasma damage."[184]

Lee, Kanarik and Gottscho (2014) "review four key areas in etch manufacturing: uniformity, defects, surface precision and 'sticky'/non-volatile etch materials"[185]. In the uniformity section, Lee, Kanarik and Gottscho discuss "the challenges for microscopic uniformity, such as localized feature dimension variations; macroscopic uniformity, such as performance at the extreme edge of the wafer; and repeatable uniformity, meaning wafer-to-wafer, lot-to-lot and chamber-to-chamber performance. While defect management is successful with in situ plasma cleans, one must be cognizant of the choice of clean chemistry."[186] In surface precision, Lee,

---

[181] Bond, LJ. 2014. Through the Looking Glass: The Future for NDE?. 40th Annual Review of Progress in Quantitative Nondestructive Evaluation: Incorporating The 10th International Conference on Barkhausen Noise and Micromagnetic Testing, vols 33a & 33b, Jul 21–26, 2013, page 21 [7]

[182] Bond, LJ. 2015. Needs and opportunities: nondestructive evaluation for energy systems. Smart Materials and Nondestructive Evaluation for Energy Systems 2015, Mar 09–10, 2015, page 943902-1 [8]

[183] Profijt, HB; Potts, SE; van de Sanden, MCM; Kessels, WMM. 2011. Plasma-Assisted Atomic Layer Deposition: Basics, Opportunities, and Challenges. J. Vac. Sci. Technol. A, vol. 29, SEP, page 050801-1 [115]

[184] Ibidem.

[185] Lee, CGN; Kanarik, KJ; Gottscho, RA. 2014. The grand challenges of plasma etching: a manufacturing perspective. J. Phys. D-Appl. Phys., vol. 47, JUL 9, page 273001-1 [83]

[186] ibidem

Kanarik and Gottscho (2014) look at "the approach of atomic layer etching and how it can be successful in a manufacturing environment."[187]

The plasma-assisted ALD can provide some unique characteristics not available in thermal ALD methods. An increase in interest in this technology "is already currently manifested by the number of ALD equipment manufacturers providing dedicated plasma-assisted ALD tools, which has increased significantly in the last few years. The demand for plasma-assisted ALD equipment from industrial R&D laboratories has, in particular, appeared to be high. It is likely that this is fuelled by the fact that industrial laboratories are particularly focused on equipment that provides a high degree of flexibility in combination with a robustness of the equipment and processes. In this respect, plasma-based techniques have been well-accepted in thin film and device manufacturing"[188] (Profijt et al, 2011).

Silicon photonics

The prospects of monolithic electronics-photonics integration are quite encouraging currently. Beyond processor-to-memory interconnects, Popovic et al. (2015) approach to "photonics as a "More-than-Moore" technology promises to enable VLSI electronic-photonic chip platforms tailored to a vast array of emerging applications, from optical and acoustic sensing, high-speed signal processing, RF and optical metrology and clocks, through to analogue computation and quantum technology." [189]

The use of silicon photonics is expanding rapidly. This technology enables the integration of electronics and optics on a single chip, through the use of CMOS manufacturing infrastructure and mature microelectronics fabrication processes. "This advantageous CMOS compatibility promises a cost-effective mass production of integrated optoelectronic circuits for a wide variety of applications ranging from optical interconnects to medical screening and sensing. However, laser integration, optical coupling of devices and subsystem assembly still remain key challenges that need to be further investigated in order to achieve high-yield and reduce manufacturing costs"[190] (Romero-Garcia et al, 2015).

[187] Lee, CGN; Kanarik, KJ; Gottscho, RA. 2014. The grand challenges of plasma etching: a manufacturing perspective. J. Phys. D-Appl. Phys., vol. 47, JUL 9, page 273001-1 [83]

[188] Profijt, HB; Potts, SE; van de Sanden, MCM; Kessels, WMM. 2011. Plasma-Assisted Atomic Layer Deposition: Basics, Opportunities, and Challenges. J. Vac. Sci. Technol. A, vol. 29, SEP, page 050801-21 [115]

[189] Popovic, MA; Wade, MT; Oreutt, JS; Shainline, JM; Sun, C; Georgas, M; Moss, B; Kumar, E; Alloatti, L; Pavanello, F; Chen, YH; Nammari, K; Notaros, J; Atabaki, A; Leu, J; Stoja-novic, V; Ram, RJ. 2015. Monolithic Silicon Photonics in a Sub-100nm SOI CMOS Microprocessor Foundry: Progress from Devices to Systems. SILICON PHOTONICS X, FEB 09–12, 2015, page 93670M-1 [111]

[190] Romero-Garcia, S; Shen, B; Merget, F; Marzban, B; Witzens, J. 2015. Alignment Tolerant Couplers for Silicon Photonics. IEEE J. Sel. Top. Quantum Electron., vol. 21, NOV–DEC, page 8200214-1 [119]

"While silicon photonics can share the technology platform developed for advanced CMOS devices it has specific dimension control requirements. Though the device dimensions are in the order of the wavelength of light used, the tolerance allowed can be less than 1 % for certain devices. Achieving this is a challenging task which requires advanced patterning techniques along with process control. Another challenge is identifying an overlapping process window for diverse pattern densities and orientations on a single layer."[191] "Using the wafer and patterning technology similar to advanced CMOS technology brings silicon photonics closer toward an integrated optical interconnect"[192] (Selvaraja et al, 2014). Popovic et al. (2015) review "recent progress of an effort led by the Stojanovic (UC Berkeley), Ram (MIT) and Popovic (CU Boulder) research groups to enable the design of photonic devices, and complete on-chip electro-optic systems and interfaces, directly in standard microelectronics CMOS processes in a microprocessor foundry, with no in-foundry process modifications. This approach allows tight and large-scale monolithic integration of silicon photonics with state-of-the art (sub-100nm-node) microelectronics, here a 45nm SOI CMOS process. It enables natural scale-up to manufacturing, and rapid advances in device design due to process repeatability. The initial driver application was addressing the processor-to-memory communication energy bottleneck."[193]

Condition monitoring is increasingly benefitting from the application of emerging technologies, such as mobile computing and wireless sensors, including photonics sensors. Emmanouilidis and Riziotis (2015) argue that photonics sensors "can be applicable to diverse application needs, due to their versatility, low costs, installation and operational flexibility, as well as unique safety and reliable operation characteristics in real industrial environments of excessive electromagnetic interference and noise. Coupling the monitoring flexibility offered by photonics technologies with the data transmission flexibility of wireless networking provides opportunities to develop hybrid wireless sensor solutions, incorporating optical sensors into wireless condition monitoring architectures"[194] (Emmanouilidis and Riziotis, 2015).

---

191 Selvaraja, SK; Winroth, G; Locorotondo, S; Murdoch, G; Milenin, A; Delvaux, C; Ong, P; Pathak, S; Xie, WQ; Sterckx, G; Lepage, G; Van Thourhout, D; Bogaerts, W; Van Cam-penhout, J; Absil, P. 2014. 193nm immersion lithography for high performance silicon photonic circuits. OPTICAL MICROLITHOGRAPHY XXVII, FEB 25–27, 2014, page 90520F-1 [126]

192 ibidem

193 Popovic, MA; Wade, MT; Oreutt, JS; Shainline, JM; Sun, C; Georgas, M; Moss, B; Kumar, E; Alloatti, L; Pavanello, F; Chen, YH; Nammari, K; Notaros, J; Atabaki, A; Leu, J; Stoja-novic, V; Ram, RJ. 2015. Monolithic Silicon Photonics in a Sub-100nm SOI CMOS Microprocessor Foundry: Progress from Devices to Systems. SILICON PHOTONICS X, FEB 09–12, 2015, page 93670M-1 [111]

194 Emmanouilidis, C; Riziotis, C. 2015. Wireless Condition Monitoring Integrating Smart Computing and Optical Sensor Technologies. ENGINEERING ASSET MANAGEMENT – SYSTEMS, PROFESSIONAL PRACTICES AND CERTIFICATION, OCT 30–NOV 01, 2013, page 1389 [38]

Emmanouilidis and Riziotis (2015) present “ongoing work within an integrated architecture for condition monitoring and maintenance management support, exploiting the added value of optical technology, inherently safe with respect to electromagnetic compatibility.”[195] “The industrial test cases are from a lift manufacturing industry, focusing on both production facilities assets, as well as on the end-product. The photonic platform of plastic optical fibres was selected due to its versatility and suitability for rapid customization and prototyping. The platform can serve diverse sensing and monitoring needs, ranging from physical parameters as strain and displacement in machinery parts, to chemical and biochemical monitoring of industrial-grade coolants’ aging. Use of novel nanostructured optical materials together with laser-based micromachining techniques enabled the functional enhancement through rapid prototyping of optical fibre devices towards highly-customizable sensors. The integration of the sensing elements within the wireless sensor network architecture offers substantial flexibility for industrial applications.”[196]

2.3.2 Additive manufacturing

Additive technology can be judged on several parameters such as surface finish, tensile strength of the product manufactured, intricacy of design, variety of materials with which the technology can work etc. (Angrish, 2014). “Additive manufacturing (AM) technology helps to reduce design error and production delay to the barest minimum. It is used to reduce cost and lead time, and it has less environmental impact. Production of a new type of product that would be impractical or difficult to manufacture through traditional method has been successfully produced using AM technology. Additive manufacturing provides opportunity for production of high value custom and limited edition products. It has the potential to reduce the carbon footprint through the elimination of energy-intensive manufacturing processes”[197] (Mahamood et al, 2014).

Chhabra and Singh (2011) review “the industrial applications of state-of-the-art additive manufacturing techniques in metal casting technology. An extensive survey of concepts, techniques, approaches and suitability of various commercialised rapid casting (RC) solutions with traditional casting methods is presented.”[198] “The information available in Chhabra and Singh serve the purpose of researchers and academicians to explore the new options in the field of rapid casting and especially users, manufacturers and service industries to produce casting in rela-

[195] Emmanouilidis, C; Riziotis, C. 2015. Wireless Condition Monitoring Integrating Smart Computing and Optical Sensor Technologies. ENGINEERING ASSET MANAGEMENT – SYSTEMS, PROFESSIONAL PRACTICES AND CERTIFICATION, OCT 30–NOV 01, 2013, page 1389 [38]

[196] Ibidem.

[197] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Ma-nufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 166 [94]

[198] Chhabra, M; Singh, R. 2011. Rapid casting solutions: a review. Rapid Prototyping J., vol. 17, 5, page 328 [21]

tively much shorter time and at low cost and even to cast complex design components which otherwise was impossible by using traditional casting processes and CNC technology."[199]

The increased number of applications for additive manufacturing technologies and the demand for parts produced with high accuracy and better quality require more precise manufacturing equipment. To address this improvement, the main goal of Cunico and de Carvalho (2013) is to "provide a systematic approach for designing additive manufacturing machines, allowing the identification of the relationship between estimated errors and the cost of equipment. In the same way, the study also intends to indicate a suitable configuration of a machine as a function of final accuracy and total equipment cost." [200]

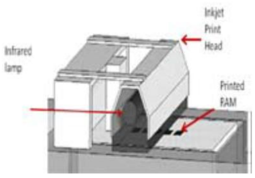
Table 7 gives comprehensive information about the AM technologies explained above "with the processes involved, machines used for these technologies, working principles, advantages, disadvantages and areas of application"[201] (Mahamood et al, 2014). Similarly, Gmeiner et al. (2015) review "the application of a broad range of additive manufacturing technologies, including Stereolithographic Ceramic Manufacturing (SLCM/LCM), 3D-Printing, indirect and direct Selective Laser Sintering/Melting (SLS/SLM), Dispense Plotting and Inkjet Plotting on bioactive glasses (BGs) and silicate bioceramics to fabricate a variety of dense and porous structures for biomedical applications (e.g. bone replacement materials)."[202]

Table 7. List of Additive Manufacturing Technologies (source: Mahamood et al, 2014)[203]

Technology	Machine	Working principle	Materials	Advantages	Disadvantages	Application field
Stereolithography (SLA)		Laser is selectively scanned onto photosensitive polymer	Photopolymer	Good surface finish, fully automated, high resolution, most widely used	Curling and wrapping problem, post curing required, limited material, high cost, highly toxic material.	Prototypes, casting pattern, medicine.

[199] Chhabra, M; Singh, R. 2011. Rapid casting solutions: a review. Rapid Prototyping J., vol. 17, 5, page 328 [21]
[200] Cunico, MWM; de Carvalho, J. 2013. Design of an FDM positioning system and application of an error-cost multi-objective optimization approach. Rapid Prototyping J., vol. 19, 5, page 344 [30]
[201] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 166 [94]
[202] Gmeiner, R; Deisinger, U; Schonherr, J; Lechner, B; Detsch, R; Boccaccini, AR; Stampfl, J. 2015. Additive Manufacturing of Bioactive Glasses and Silicate Bioceramics. J. Ceram. Sci. Technol., vol. 6, JUN, pp. 75–86 [58]
[203] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 166 [94]

Technology	Machine	Working principle	Materials	Advantages	Disadvantages	Application field
Selective Laser Sintering (SLS)		Heated laser is used to sinter particles together	Polycarbonate, nylons, elastomers, ceramics, metals	Wide material range, requires no support structure during building processes, stronger part can be produced, requires no post curing, part can be built on top of an existing part.	Requires lots of time for heating below melting and subsequent part cooling, surface finish depend on powder size, high running cost because of the use of	Nitrogen, generation of toxic gases (Knox) hence environmental issues.
Fused Deposition Modelling (FDM)		Filament is extruded through heated nozzle	Thermoplastic, wax, ABS, elastomers	Use of different colours are possible, material can be changed quickly, fast, does not require clean-up	Accuracy depends on material size; require support, weak part, delamination problem resulting from poor temperature control.	Model, assembly testing, investment casting, injection moulding
Laminated Object Manufacturing (LOM)		Laser is used to cut cross sections out of layers of material; layers are thermally fused together	Paper, plastic, ceramic and metal powder tape	Faster cheaper, good for building large part,	Cannot produce hollow part, strength depend on bonding strength	Prototype, models, pattern for injection moulding
Solid Ground Curing (SGC)		Used electro photography technique to print mask and cured the entire layer at once	Photopolymer	High throughput, require no support structure, no post curing required, build process can be interrupted and adjusted	Requires attention, requires skill, noisy operation, high equipment cost	Prototypes, casting pattern, Medicine.
Ink-Jet Printing		Printer head is used to deposits molten material	Plastic, wax, plaster, bronze	Fine resolution, good surface finish	Fragile part, noisy in operation, slow for large part prototypes, model, casting pattern	Technology process
Laser Engineered Net Shape		High laser power is used to melt metal powder supplied coaxially to the focus of the laser beam.	Metals	Material composition can be changed dynamically, can make fully dense part with good grain	Requires finish machining.	Near net shape object can be produced

Technology	Machine	Working principle	Materials	Advantages	Disadvantages	Application field
				structure, requires no post processing firing		
Infra-Red & Masking Systems		Use infrared radiation to fuse the powder layer through the negative masks printed under glass plate.	Polymer, metal, ceramic	Faster, low running cost	Radiation absorption depends on colour of material, i.e. darker colour absorbs more than brighter colours	Prototypes, injection moulds, Aeronautics, Automobile, Medicine

Some newer additive manufacturing technologies such as laser consolidation have the potential to repair broken metal components by printing the damaged areas over the existing metal bodies. "Capabilities of this kind will not only enable companies to reduce their time to development but will also reuse some of the critical and non-critical components at very low costs."[204] Angrish (2014) looks at "the different additive manufacturing technologies which can be used for the manufacturing of aerospace components from a number of different parameters, their advantages and disadvantages and tries to assess their feasibility for production of components for practical applications. Apart from this, the paper also covers the latest developments in this field and assesses what will be their implications on the management of critical components for use in the aerospace sector."[205]

Though additive manufacturing offers a wide range of advantages over traditional manufacturing techniques, its industrial application is still, however, in its infancy. Despite all the benefits derived from AM technology, there are still many unresolved issues with the technology that has hindered its performance, thereby limiting its application to high tolerant jobs, that is, jobs that allow poor dimensional accuracy or poor surface finish, for example (Wang and Yuan, 2014). Ahuja, Karg and Schmidt (2015) discuss some of "the key challenges which are critical to ensure that Additive Manufacturing is truly accepted as a mainstream production technology in the industry. These challenges highlight various aspects of production such as product requirements, process management, data management, intellectual property, work flow management, quality assurance, resource planning, etc. In addition, changing market trends such as product life cycle, mass customization, sustainability, environmental impact and localized production form the foundation for the follow up discussion on the current limitations and the

[204] Angrish, A. 2014. A Critical Analysis of Additive Manufacturing Technologies for Aerospace Applications. 2014 IEEE AEROSPACE CONFERENCE, MAR 01–08, 2014, page 1 [2]

[205] Angrish, A. 2014. A Critical Analysis of Additive Manufacturing Technologies for Aerospace Applications. 2014 IEEE AEROSPACE CONFERENCE, MAR 01–08, 2014, page 1 [2]

corresponding research opportunities. A discussion on ongoing research to address these challenges includes topics such as process monitoring, design complexity, process standardization, multi-material and hybrid fabrication, new material development, etc."[206]

Cooper and Wachter (2014) argue that "for AM to be commercially accepted, it must make products reliably and predictably. AM processes must achieve consistency and be reproducible."[207] "The development of cyber-enabled manufacturing system concepts for AM should address issues such as part quality and process dependability, which are the keys to successful application of this disruptive rapid manufacturing technology."[208] "Repeatability is also a major concern which has caused the technology not to be fully accepted. Repeatability is a major concern of AM technology as a result of highly sensitive nature of AM technologies to environmental variation"[209] (Mahamood et al, 2014). There is always a variation in part produced at constant process parameters (Wang and Yuan, 2014). Moreover, "the lack of standards in AM impedes its use for parts production, since industries primarily depend on established standards in processes and material selection to ensure the consistency and quality"[210] (Mani et al, 2014).

However, productivity of AM process is still low, especially for simple large volume parts. "Despite different research effort in improving speed of AM, not much has been achieved. It is still below what is considered acceptable for mass production. There are a number of issues that need to be resolved before AM can compete with traditional method such as casting in terms of mass production. All the associated technologies (Laser, materials, etc.) need improvement" (Mahamood et al, 2014). [211]

For example, performance of 3D-printed fuel cells and stacks is lacking. Gould et al. (2014) "use the AM method of direct metal laser sintering (DMLS) to make 21 cm 2 titanium-alloy BPPs with embedded flow channels."[212] "The resulting 400 W fuel cell stack power is 20 % less than expected because of inadequate flatness of several of the DMLS BPPs as determined by

---

[206] Ahuja, B; Karg, M; Schmidt, M. 2015. Additive Manufacturing in Production – Challenges and Opportunities. LASER 3D MANUFACTURING II, FEB 10–12, 2015, page 1 [1]

[207] Cooper, KP; Wachter, RF. 2014. Cyber-enabled manufacturing systems for additive manufacturing. Rapid Prototyping J., vol. 20, 5, page 355 [27]

[208] ibidem

[209] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 167 [94]

[210] Mani, M; Lyons, KW; Gupta, SK. 2014. Sustainability Characterization for Additive Manufacturing. J. Res. Natl. Inst. Stand. Technol., vol. 119, SEP 22, page 419 [96]

[211] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 167 [94]

[212] Gould, BD; Rodgers, JA; Schuette, M; Bethune, K; Louis, S; Rocheleau, R; Swider-Lyons, K. 2014. Performance of 3D-printed fuel cells and stacks. POLYMER ELECTROLYTE FUEL CELLS 14, OCT 05–09, 2014, page 935 [60]

white light profilometry, leading to high contact resistance."[213] While "DMLS clearly shows the benefit of being able to make complex flow fields and hollow parts with no welds,"[214] "more work is needed toward reducing the weight and increasing the flatness of BPPs made by AM."[215]

Hergel and Lefebvre (2014) review the current state of Fused Filament Fabrication. It is "an additive manufacturing process by which a 3D object is created from plastic filament. The filament is pushed through a hot nozzle where it melts. The nozzle deposits plastic layer after layer to create the final object. This process has been popularized by the RepRap community. Several printers feature multiple extruders, allowing objects to be formed from multiple materials or colours. The extruders are mounted side by side on the printer carriage. However, the print quality suffers when objects with colour patterns are printed – a disappointment to designers interested in 3D printing their coloured digital models. The most severe issue is the oozing of plastic from the idle extruders: Plastics of different colours bleed onto each other giving the surface a smudged aspect, excess strings oozing from the extruder deposit on the surface, and holes appear due to this missing plastic. Fixing this issue is difficult: increasing the printing speed reduces oozing but also degrades surface quality – on large prints the required speed level become impractical. Adding a physical mechanism increases cost and print time as extruders travel to a cleaning station"[216] (Hergel and Lefebvre, 2014).

Cooper (2014) points out that "successes of Additive Manufacturing are tempered by challenges facing practitioners such as process and part qualification and verification, which are needed to develop AM as a true manufacturing technology"[217]. Similarly, Mahamood et al. (2014) take a look at "some important AM technologies, problems currently facing AM technology at large and proposes solutions to these problems."[218] "A major known drawback in AM is poor dimensional accuracy and poor surface finish; only the layer height and melt pool temperature are controlled to resolve this problem in the literature. The stair-stepping effect in adaptive manufacturing is rooted in a natural phenomenon of surface tension which is the

[213] Gould, BD; Rodgers, JA; Schuette, M; Bethune, K; Louis, S; Rocheleau, R; Swider-Lyons, K. 2014. Performance of 3D-printed fuel cells and stacks. POLYMER ELECTROLYTE FUEL CELLS 14, OCT 05–09, 2014, page 935 [60]
[214] ibidem
[215] ibidem
[216] Hergel, J; Lefebvre, S. 2014. Clean color: Improving multi-filament 3D prints. Comput. Graph. Forum, vol. 33, MAY, page 469 [65]
[217] Cooper, KP. 2014. Laser-based additive manufacturing: Where it has been, where it needs to go. LASER 3D MANUFACTURING, FEB 05–06, 2014, page 897003-1 [26]
[218] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 161 [94]

cause of the poor surface finish and, in combination with other factors, is responsible for the poor dimensional accuracy."[219]

Consequently, Everton et al. (2015) argue that, "in order for the benefits of Additive Manufacturing to be realised, further development and integration of suitable monitoring and closed loop control systems are needed. Laser Ultrasonic Testing (LUT) is an inspection technology which shows potential for in-situ monitoring of metallic AM processes. Non-contact measurements can be performed on curved surfaces and in difficult-to-reach areas, even at elevated temperatures. Interrogation of each build layer generates defect information which can be used to highlight processing errors and allow for real-time modification of processing parameters, enabling improved component quality and yield."[220] "Traditional Non-Destructive Evaluation (NDE) methods could be utilized in both in-process and post-process applications, although currently there are very few examples of in-situ sensors for monitoring AM processes"[221] (Slotwinski, 2014).

Uriondo, Esperon-Miguez and Perinpanayagam (2014) review "recent improvements in additive manufacturing technologies, focusing on those which have the potential to produce and repair metal parts for the aerospace industry. Electron beam melting, selective laser melting and other metal deposition processes, such as wire and arc additive manufacturing, are presently regarded as the best candidates to achieve this challenge. For this purpose, it is crucial that these technologies are well characterised and modelled to predict the resultant microstructure and mechanical properties of the part."[222] Uriondo, Esperon-Miguez and Perinpanayagam (2014) present "the state of the art in additive manufacturing and material modelling. While these processes present many advantages to the aerospace industry in comparison with traditional manufacturing processes, airworthiness and air transport safety must be guaranteed. The impact of this regulatory framework on the implementation of additive manufacturing for repair and production of parts for the aerospace industry is presented."[223]

[219] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 161 [94]

[220] Everton, S; Dickens, P; Tuck, C; Dutton, B. 2015. Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing. LASER 3D MANUFACTURING II, FEB 10–12, 2015, page 935316-1 [50]

[221] Slotwinski, JA. 2014. Additive Manufacturing: Overview and NDE Challenges. 40TH ANNUAL REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE EVALUATION: INCORPORATING THE 10TH INTERNATIONAL CONFERENCE ON BARKHAUSEN NOISE AND MICROMAGNETIC TESTING, VOLS 33A & 33B, JUL 21–26, 2013, page 1173 [134]

[222] Uriondo, A; Esperon-Miguez, M; Perinpanayagam, S. 2014. The present and future of additive manufacturing in the aerospace sector: A review of important aspects. Proc. Inst. Mech. Eng. Part G-J. Aerosp. Eng., vol. 229, SEP, page 2132 [143]

[223] ibidem

2.3.3 Advanced machinery

Robot control

Robot control is a key element in robot performance. A great deal of development work is done to reduce robot cost and introduce new functionalities. Some of the development areas that currently attract a great deal of attention are multi robot control, safe control, force control, 3D vision, remote robot supervision and wireless communication (Brogardh, 2007). "For practical applications, an industrial robot system is a highly nonlinear, time-varying and coupling system. In order to satisfy the requirement of high performance, the design of controllers is a challenge, especially to control a kind of track motion robot with different working frequencies for the combination of track motion and machine vision, the degree of difficulty for stable control must be raised very much"[224] (Liu et al, 2012).

Similarly, "the vision-based bin picking using object recognition has been considered as an innovative manufacturing process in industrial robotics applications. In a bin picking system, pick and place tasks are performed by a robot which has been processed by measuring object pose. But it has to address challenging problems such as object appearance distorted by overlapping parts, lighting variation or reflection, picking from randomly piled parts in a bin"[225] (Kim et al, 2012).

Accuracy of operations

Improved application of measurement is a major enabler of mass production (Shore and Morantz, 2012). "Recently, new needs have emerged to control not only linear motion but also rotational motion in high-accuracy manufacturing fields"[226] (Wu et al, 2012). "Robotic solutions for propeller measurement have not been successfully implemented within marine propellers finishing due to reasons like lack of accuracy and repeatability"[227]. Cavada and Fadon (2013) analyse "the root causes of this problem, identifying the calibration process, the cell alignment

---

[224] Liu, CS; Liu, CC; Tai, YH; Lin, GZ. 2012. Implementation and Control for a Track Motion Robotic Manipulator. 2012 PROCEEDINGS OF SICE ANNUAL CONFERENCE (SICE), AUG 20–23, 2012, page 552 [91]

[225] Kim, K; Kim, J; Kang, S; Kim, J; Lee, J. 2012. Vision-Based Bin Picking System for Industrial Robotics Applications. 2012 9TH INTERNATIONAL CONFERENCE ON UBIQUITOUS ROBOTS AND AMBIENT INTELLIGENCE (URAL), NOV 26–29, 2012, page 515 [77]

[226] Wu, W; Hirogaki, T; Aoyama, E. 2012. Investigation of Synchronous Accuracy of Dual Arm Motion of Industrial Robot. PROCEEDINGS OF PRECISION ENGINEERING AND NANOTECHNOLOGY (ASPEN2011), NOV 16–18, 2011, pp. 234–239

[227] Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, page 275 [15]

method and the tool positioning as the principal factors resulting in this low measuring repeatability."[228]

According to Cavada and Fadon (2013), geometrical diversity is a considerable challenge when traditionally manual manufacturing processes such as hand-grinding and polishing need to be automated."[229] Cavada and Fadon (2013) discuss the case of marine propellers. "Majority of the propellers being produced worldwide are custom-designed products aiming to satisfy each ship's propulsion requirements. In several market-leading propeller manufacturers within Europe and Asia, industrial robots are being applied in widely diverse operations such as milling polystyrene blocks to make moulding patterns, grinding out the excess material in the blade surfaces, or polishing the complete propeller surface before its final verification. Propeller blades are customized products, formed by curved and warped surfaces, requiring minimum 5 axes to be smoothly polished, and this can easily be achieved with a robot cell where the CAD/CAM data coming from the individual design are directly translated into robotic parameters."[230]

Indeed, "the industrial robot accuracy can vary over a very wide range in the workspace. This provides an additional opportunity to increase the reliability of the assembly process through the appropriate choice of the point of parts joining."[231] Kluz and Trzepiecinski (2014) present "a methodology that allows the designer of assembly workstations to rapidly estimate the repeatability of robot positioning and to allocate at the design stage of assembly process the optimal position in the robot workspace so as to ensure the required precision, without unnecessarily high accuracy of equipment being used and, therefore, without inflated costs."[232]

Shore and Morantz (2012) identify "the ambitions of the defence, automotive and microelectronics sectors as important drivers of improved manufacturing accuracy capability and ever-smaller feature creation. It then describes how science fields such as astronomy have presented significant precision engineering challenges, illustrating how these fields of science have achieved unprecedented levels of accuracy, sensitivity and sheer scale."[233]

---

[228] Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, page 275 [15]

[229] Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, page 275 [15]

[230] Ibidem.

[231] Kluz, R; Trzepiecinski, T. 2014. The repeatability positioning analysis of the industrial robot arm. Assem. Autom., vol. 34, 3, page 285 [78]

[232] Ibidem.

[233] Shore, P; Morantz, P. 2012. Ultra-precision: enabling our future. Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci., vol. 370, AUG 28, page 3993 [128]

Machine flexibility and availability

Today, manufacturing operations that require both high stiffness and accuracy are typically realized with computer numerical control machine tools." Caro et al. (2014) show that "manufacturing finishing tasks can be performed with robotic cells knowing the process cutting conditions and the robot stiffness throughout its workspace. It makes sense that the finishing task of large parts should be cheaper with robots. However, machining robots have not been adapted for such operations yet." [234] Caro et al. (2014) "introduce a methodology that aims to determine the best placement of the workpiece to be machined knowing the elastostatic model of the robot and the cutting forces exerted on the tool."[235]

The manufacturing of multi-material composites provides another challenge. It requires a lot of manual labour and is typically requiring tools resulting in added costs. "A combination or integration of additive and composite manufacturing is limited or even non-existent, being an indicator for the difficulties of bringing these two technologies together."[236] However, "these composites, consisting of a matrix and embedded fibres, are increasingly used in various industries, and not just the aerospace and automotive industry"[237] (Fischer et al, 2013).

Machine manufactures must on one hand lower the prices, but then on the other hand improve machine flexibility and availability. Industrial Powerline Communication (IPLC) can play an elemental role here by simultaneously reducing the costs and increasing flexibility. Lopes, Wurst and Verl (2013) "merge the requirements and constraints of Powerline Communication (PLC) and Industrial Communication and propose a solution to this problem. This solution consists of ferrite filtering, with the task of building a Daisy Chain Network topology on top of a PLC bus." [238]

The use of linear motor drives (LMDs) is "severely limited by their tendency to consume a great deal of electrical energy and cause thermal issues, particularly under high cutting loads. A hybrid feed drive (HFD) has recently been proposed as a potential solution to this dilemma. The HFD switches between LMD and SD actuation depending on the mode of the manufactur-

---

[234] Caro, S; Garnier, S; Furet, B; Klimchik, A; Pashkevich, A. 2014. Workpiece Placement Optimization for Machining Operations with Industrial Robots. 2014 IEEE/ASME INTERNATIONAL CONFERENCE ON ADVANCED INTELLIGENT MECHATRONICS (AIM), JUL 08–11, 2014, page 1716 [14]

[235] Ibidem.

[236] Fischer, A; Rommel, S; Bauernhansl, T. 2013. New Fiber Matrix Process with 3D Fiber Printer A Strategic In-process Integration of Endless Fibers Using Fused Deposition Modeling (FDM). DIGITAL PRODUCT AND PROCESS DEVELOPMENT SYSTEMS, OCT 10–11, 2013, page 167 [55]

[237] Fischer, A; Rommel, S; Bauernhansl, T. 2013. New Fiber Matrix Process with 3D Fiber Printer A Strategic In-process Integration of Endless Fibers Using Fused Deposition Modeling (FDM). DIGITAL PRODUCT AND PROCESS DEVELOPMENT SYSTEMS, OCT 10–11, 2013, page 167 [55]

[238] Lopes, J; Wurst, KH; Verl, A. 2013. Industrial Powerline Communication for Machine Tools and Industrial Robots. 2013 17TH IEEE INTERNATIONAL SYMPOSIUM ON POWER LINE COMMUNICATIONS AND ITS APPLICATIONS (ISPLC), MAR 24–27, 2013, page 351 [93]

ing operation, thus achieving speeds and accuracies similar to LMDs while consuming much less energy."[239] Kale, Dancholvichit and Okwudire (2014) present "a comparative life cycle analysis (LCA) of the proposed HFD with an LMD as the baseline for the comparison."[240] "The analysis predicts a net positive impact in terms of energy and the environment, for the HFD compared to the LMD under high cutting loads."[241]

In order to improve the sustainability of manufacturing, one needs to solve the environmental impact of lubricants. "Even if dry cutting can be identified as the ultimate goal to achieve, lubrication is still a scarcely surmountable industrial standard when machining difficult-to-cut alloys. In order to reduce the pollutant emissions and the problems related to the workers' health, alternative systems as Minimum Quantity Lubrication (MQL) or Cooling (MQC) have been emerging over the years"[242] (Priarone et al, 2013).

2.4 Summary: Barriers and drivers in high performance manufacturing

2.4.1 Micro & nano manufacturing

There are a number of factors that drive developments in micro and nano manufacturing. Typically, these are related to the desire to better meet the customers' needs. For example, medical applications need to provide biocompatibility, the highest miniaturization, rough treatment, autoclave sterilization and resistance towards harsh environments to be applicable (Braun et al, 2012; Sidambe, 2014). Similarly, "coupling the monitoring flexibility offered by photonics technologies, with the data transmission flexibility of wireless networking provides opportunities to develop hybrid wireless sensor solutions."[243] This provides "versatility, low costs, installation and operational flexibility, as well as unique safety and reliable operation characteristics in real industrial environments of excessive electromagnetic interference and noise"[244] (Emmanouilidis and Riziotis, 2015).

---

[239] Kale, S; Dancholvichit, N; Okwudire, C. 2014. Comparative LCA of a linear motor and hybrid feed drive under high cutting loads. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, page 552 [74]

[240] Kale, S; Dancholvichit, N; Okwudire, C. 2014. Comparative LCA of a linear motor and hybrid feed drive under high cutting loads. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, page 552 [74]

[241] Ibidem.

[242] Priarone, PC; Robiglio, M; Settineri, L; Tebaldo, V. 2015. Effectiveness of minimizing cutting fluid use when turning difficult-to-cut alloys. 22ND CIRP CONFERENCE ON LIFE CYCLE ENGINEERING, APR 07–09, 2015, page 341 [114]

[243] Emmanouilidis, C; Riziotis, C. 2015. Wireless Condition Monitoring Integrating Smart Computing and Optical Sensor Technologies. ENGINEERING ASSET MANAGEMENT – SYSTEMS, PROFESSIONAL PRACTICES AND CERTIFICATION, OCT 30–NOV 01, 2013, page 1389 [38]

[244] Ibidem

Micro-scale structures lead to higher frequency operation and lower power consumption. In micro-mechanics, small feature size “structures have low mass and high resonant frequencies, enabling high sensitivity yet robust operation. In micro-fluidics, micro-channels exhibit high laminar flow, providing the potential for chemistry at molecular scales and the ability to single out and manipulate individual living cells”[245] (Topham and Harrison, 2008). Similarly, monolithic electronics-photonics integration enables the integration of electronics and optics on a single chip, using CMOS manufacturing infrastructure and mature microelectronics fabrication processes, and promises to enable “platforms tailored to a vast array of emerging applications, from optical and acoustic sensing, high-speed signal processing, RF and optical metrology and clocks, through to analogue computation and quantum technology”[246] (Bechtold, 2009).

Moreover, there is great “potential of different nano-particles as additives for plastic packaging materials for enhanced humidity resistance/barrier enhancement”[247]: e.g. plastic packaging materials with enhanced humidity resistance increase package reliability during assembly and lifetime without cost increase and with no changes in processing (Braun et al, 2008).

However, there are barriers to the adoption of micro and nano manufacturing technologies also. One barrier is the complexity of the high-precision assembly process itself. It is challenging to build a physical model to establish the relationship between an assembly process and its process parameters (Li et al, 2014). Also, “there are formidable challenges in the conception and design of whole products and systems.”[248] It is challenging to side-stepping packaging and interconnection to integrating micro-capabilities directly into macro products. This means leaving behind component-level hierarchical design and manufacture and adopting a holistic approach to both (Topham and Harrison, 2008). Finally, there is a need for better detection and classification of defects, as well as, for improvement in the reliability of inspection and probability of detection (Bond, 2015).

Laser integration, optical coupling of devices and subsystem assembly still remain key challenges that need to be further investigated in order to achieve high-yield and to reduce micro and nano manufacturing costs (Romero-Garcia et al, 2015). Similarly, “the integration of micro-components into macro-scale products is non-trivial, conventionally posing difficult questions

[245] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from in-tegrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, page 1311 [139]

[246] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Techno-logies. 2009 EUROPEAN MICROELECTRONICS AND PACKAGING CONFERENCE (EMPC 2009), VOLS 1 AND 2, JUN 16–18, 2009, page 798 [4]

[247] Braun, T; Hausel, F; Bauer, J; Wittler, O; Mrossko, R; Bouazza, M; Becker, KF; Oester-mann, U; Koch, M; Bader, V; Minge, C; Aschenbrenner, R; Reichl, H. 2008. Nano-particle enhanced encapsulants for improved humidity resistance. 58TH ELECTRONIC COMPONENTS & TECHNOLOGY CONFERENCE, PROCEEDINGS, 2008, page 198 [10]

[248] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from in-tegrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, page 1311 [139]

and compromises in the domains of packaging, interconnection and design”[249]: “system-in-package integration capabilities require thermal management, temperature resistivity and heterogeneous system integration”[250] (Topham and Harrison, 2008; Bechtold, 2009).

Table 8. Barriers and drivers in high performance manufacturing, micro & nano manufacturing

	Barriers	Drivers
Environmental Context	• The basic processes common to manufacturing-qualification of raw materials, continuous synthesis methods, process monitoring and control, in-line and off-line characterization of product for quality control purposes, validation by standard reference materials are not generally in place for nanotechnology based products	• Adapted digital workflow promises advantages in the introduction of process documentation, aspects of quality control, cost minimization and in the efficiency improvement
Organizational Context	• Challenges in the conception and design of whole products and systems: challenging to side-stepping packaging and interconnection to integrating micro-capabilities directly into macro products, means leaving behind component-level hierarchical design and manufacture and adopting a holistic approach to both	
Technological Context	• The integration of micro-components into macro-scale products is non-trivial, conventionally posing difficult questions and compromises in the domains of packaging, interconnection and design: system in package integration capabilities require thermal management, temperature resistivity and heterogeneous system integration • Laser integration, optical coupling of devices and subsystem assembly still remain key challenges that need to be further investigated in order to achieve high-yield and reduce manufacturing costs • Complexity of high precision assembly process: challenging to build a physical model to establish the relationship between an assembly process and its process parameters • Need to develop the basic manufacturing metrology infrastructure to implement fundamental best practices for manufacturing and in the determination of properties for nanoscale materials and the re-	• Monolithic electronics-photonics integration promises to enable platforms tailored to a vast array of emerging applications, from optical and acoustic sensing, high-speed signal processing, RF and optical metrology and clocks, through to analogue computation and quantum technology • Incorporating optical sensors into wireless condition monitoring architectures provides versatility, low costs, installation and operational flexibility, as well as safety and reliable operation characteristics in industrial environments • New materials can add new functionalities, such as on-chip photonics, which can vastly improve interchip interconnects • Different nano-particles as additives for plastic packaging materials for enhanced humidity resistance/barrier enhancement: e.g. increase package reliability during assembly and lifetime without cost increase and with no changes in processing

[249] Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from in-tegrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, page 1311 [139]

[250] Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Techno-logies. 2009 EUROPEAN MICROELECTRONICS AND PACKAGING CONFERENCE (EMPC 2009), VOLS 1 AND 2, JUN 16–18, 2009, page 798 [4]

	sultant products • Difficulty in detecting, sizing and typing defects, need to improve the reliability of inspection and probability of detection	• Plasma processing promises a wider choice in material properties, substrate temperature, choice of precursors and processing conditions: plasma-based techniques provide a high degree of flexibility in combination with a robustness of the equipment and processes

2.4.2 Additive manufacturing

There are still many unresolved issues that have hindered additive manufacturing's performance, thereby limiting its application to high tolerant jobs. These challenges highlight various aspects of production such as product requirements, process management, data management, intellectual property, work flow management, quality assurance, resource planning, etc. Productivity of the additive manufacturing process is still very low, especially for simple large-volume parts. Products must be made reliably and predictably. Another major known drawback in additive manufacturing is poor dimensional accuracy and poor surface finish (Mahamood et al, 2014). Hence, "monitoring and closed loop control systems are needed"[251] (Everton et al, 2015). The lack of standards in additive manufacturing impedes its use for parts production, since "industries primarily depend on established standards in processes and material selection in order to ensure the consistency and quality"[252] (Mani et al, 2014).

In order to ease the implementation of additive manufacturing technologies, DARPA now addresses the systematic barriers to implementation rather than the technology itself: the Open Manufacturing programme is enabling rapid qualification of new technologies for the manufacturing environment. Moreover, it is expected that developing computational, communicational and control approaches of additive manufacturing will help validate and move it to the factory floor (Cooper, 2014).

The challenges in additive manufacturing relate to environment and energy, scale and cost of production and structural performance. On the other hand, additive manufacturing can reduce cost, lead time and it has less environmental impact. Additive manufacturing has the potential to reduce the carbon foot print through the elimination of energy intensive manufacturing processes. New fabrication techniques in additive manufacturing provide the necessary tools to support the need for increased flexibility and enable economic low volume production, cutting costs due to a significant reduction in material waste (Mellor et al, 2014). One driver of

[251] Everton, S; Dickens, P; Tuck, C; Dutton, B. 2015. Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing. LASER 3D MANUFACTURING II, FEB 10–12, 2015, page 1 [50]

[252] Mani, M; Lyons, KW; Gupta, SK. 2014. Sustainability Characterization for Additive Ma-nufacturing. J. Res. Natl. Inst. Stand. Technol., vol. 119, SEP 22, page 419 [96]

additive manufacturing can be the way it gives designers the opportunity to create their products in ways which were previously considered impossible to manufacture, such as customization and new design possibilities (Singh and Sewell, 2012). Indeed, "part consolidation by additive manufacturing could bring great benefits in future product design applications"[253] (Jansen et al, 2014). Additive manufacturing also "provides an opportunity for production of high value custom and limited edition products"[254] (Mahamood et al, 2014).

Table 9. Barriers and drivers in high performance manufacturing, additive manufacturing

	Barriers	Drivers
Environmental Context	• The additive manufacturing challenges relate to environment and energy, scale and cost of production and structural performance • Difficulty in developing a cost-effective solution to additive manufacturing of non-metals and metals	• Funder's focus on the systematic barriers to implementation rather than the technology itself; e.g. the Open Manufacturing programme is enabling rapid qualification of new technologies for the manufacturing environment • Developing cyber-enabled manufacturing systems: such computation, communication and control approaches will help in validating additive manufacturing and moving it to the factory floor
Organizational Context	• Lack of expert knowledge	
Technological Context	• Productivity of additive manufacturing process is still very low especially for simple large volume parts • Must make products reliably and predictably: additive manufacturing processes must achieve consistency and be reproducible • Challenges in process and part qualification and verification: a major drawback in additive manufacturing is poor dimensional accuracy and poor surface finish, monitoring and closed loop control systems are needed • Lack of standards in additive manufacturing impedes its use for parts production since industries primarily depend on established standards in processes and material selection to ensure the consistency and quality • Combination or integration of additive and composite manufacturing is very limited, being an indicator for the difficulties to bring these two technologies together	• Promises in reduced cost, lead time and lower environmental impact, has the potential to reduce the carbon foot print through the elimination of energy intensive manufacturing processes • Provides opportunity for production of high value custom and limited edition products • Gives designers the opportunity to create their products in ways which were previously considered impossible to manufacture, such as customization and new design possibilities; part consolidation by additive manufacturing could bring great benefits in future product design applications • Newer technologies such as laser consolidation have the potential to repair broken metal components by printing the damaged areas over the existing metal bodies

[253] Jansen, B; Doubrovski, EL; Verlinden, JC. 2014. Animaris Geneticus Parvus Design of a complex multi-body walking mechanism. Rapid Prototyping J., vol. 20, 4, page 311 [73]

[254] Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Ma-nufacturing: An Overview. Laser Eng., vol. 27, Apr 3, page 161 [94]

2.4.3 Advanced machinery

The emergence of cloud computing paradigm can be a driver of new high performance manufacturing systems. Cloud computing can be utilized as a hosting platform for autonomous data mining and cognitive learning algorithms. This brings “new service models and research opportunities to the manufacturing and service industries with advantages in ubiquitous accessibility, convenient scalability and mobility”[255] (Yang et al, 2015).

However, potential barriers to the implementation of high performance manufacturing include requirements for advanced planning procedures and user involvement plans, the need to improve communication, to potentially change company labour policies and to introduce continuous training programmes. Management should take timely action with regard to these (Das, 2001).

Within the Technological Context, “selection of a robot for a specific industrial application is one of the most challenging problems in the real time manufacturing environment. It has become more and more complicated due to an increase in complexity, advanced features and facilities that are continuously being incorporated into the robots by different manufacturers”[256] (Chatterjee et al, 2010). Robots have not been successfully implemented within product finishing due to reasons such as lack of accuracy and repeatability. For example, “geometrical diversity is a considerable challenge when traditionally manual manufacturing processes such as hand-grinding and polishing need to be automated”[257] (Cavada and Fadon, 2013). There can be additional challenges in advanced machinery. “An industrial part may need to be partitioned into multiple patches because of its complexity. The trajectories of all patches must then be connected in order to minimize the material waste and process cycle time”[258] (Chen and Xi, 2012).

More generally, a potential barrier to the introduction of advanced machinery can be the difficulty in managing “the ever-increasing information flow and system complexity of production

[255] Yang, SH; Bagheri, B; Kao, HA; Lee, J. 2015. A Unified Framework and Platform for De-signing of Cloud-Based Machine Health Monitoring and Manufacturing Systems. J. Ma-nuf. Sci. Eng.-Trans. ASME, vol. 137, AUG, page 040914-1 [154]

[256] Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, OCT, page 483 [18]

[257] Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, page 275 [15]

[258] Chen, HP; Xi, N. 2012. Automated Robot Tool Trajectory Connection for Spray Forming Process. J. Manuf. Sci. Eng.-Trans. ASME, vol. 134, APR, page 021017-1 [19]

cells that incorporate equipment from different producers"[259] (Chioreanu et al, 2013). The number of tasks of the same type can be limited because of the size of an SME. Robots "do not adapt well to dynamic environments, do not offer rich human-robot interaction and are not simple for end-users to program"[260] (Heyer, 2010). Flexibility and cost are important robot selection criteria for an SME. Naturally, high cost and inflexibility become barriers to the purchase decision (Bi et al, 2015). "Manufacturing environment, product design, production system and cost involved are some of the most influencing factors that directly affect the robot selection decision"[261] (Chatterjee et al, 2010).

Robot manufacturers are looking for ways to actively engage human operators in a constructive fashion. Indeed, "the integration of human operators into robot-based manufacturing systems may increase productivity by combining the abilities of machines with those of humans"[262] (Ding et al, 2011). For example, more intuitive ways are developing to programme robots (Neto, 2013).

Table 10. Barriers and drivers in high performance manufacturing, advanced machinery

	Barriers	Drivers
Environmental Context	• Difficulty in estimating the repeatability of robot positioning to ensure the required precision, without unnecessarily high accuracy of equipment used and, therefore, without inflated costs	• Promises in reduction of the pollutant emissions and the problems related to workers' health: systems as Minimum Quantity Lubrication (MQL) or Cooling (MQC) have been emerging over the years
Organizational Context	• Managerial action needed with regard to advanced planning procedures, user involvement plans, communication channels, company labour policies and continuous training programmes • Difficulty in managing information flow and system complexity of production cells that incorporate equipment from different producers • The number of tasks of the same type can be limited because of the size of an SME, hence flexibility and cost are important robot selection criteria	• Cloud computing paradigm can be utilized as a hosting platform for autonomous data mining and cognitive learning algorithms; these bring new service models in the manufacturing and service industries with advantages in ubiquitous accessibility, convenient scalability and mobility

259 Chioreanu, A; Brad, S; Brad, E. 2013. Knowledge Modelling of E-maintenance in Industrial Robotics. INTERDISCIPLINARY RESEARCH IN ENGINEERING: STEPS TOWARDS BREAKTHROUGH INNOVATION FOR SUSTAINABLE DEVELOPMENT, FEB 25–MAR 01, 2013, page 603 [22]

260 Heyer, C. 2010. Human-Robot Interaction and Future Industrial Robotics Applications. IEEE/RSJ 2010 INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2010), OCT 18–22, 2010, page 4749 [66]

261 Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, OCT, page 483 [18]

262 Ding, H; Wijaya, K; Reissig, G; Stursberg, O. 2011. Optimizing Motion of Robotic Mani-pulators in Interaction with Human Operators. INTELLIGENT ROBOTICS AND APPLICATIONS, PT I: ICIRA 2011, DEC 06–08, 2011, page 520 [34]

Technological Context	• Selection of a robot for a specific industrial application is challenging in real time manufacturing environment: It has become increasingly complicated due to an increase in complexity, advanced features and facilities that are continuously being incorporated into the robots by different manufacturers • Robots do not adapt well to dynamic environments, do not offer rich human-robot interaction and are not simple for end-users to programme • Design of controllers is a challenge to: 1) control not only linear motion but also rotational motion in high-accuracy manufacturing fields, 2) address object appearance distorted by overlapping parts, lighting variation or reflection, picking from randomly piled parts in a bin • Robots have not been successfully implemented within product finishing due to reasons like lack of accuracy and repeatability • Variations in tool life can make planning challenging, requires ensuring that there are sufficient cutting tools available on the machines to meet unsupervised production requirements	• The integration of human operators into robot-based manufacturing systems may increase productivity by combining the abilities of machines with those of humans • More intuitive ways are developing to programme robots • New capabilities for manufacturing operations and for adaptive robot performance: the robot control is optimised with respect to the best placement of the workpiece and to thermal and fatigue load on the robot • New capabilities for actuation depending on the mode of the manufacturing operation, thus achieving benchmark speeds and accuracies while consuming much less energy

3 Sustainable manufacturing technologies

3.1 Environmental Context

3.1.1 Sustainability in manufacturing

Granly and Webo (2014) seek a deeper understanding of the drivers, challenges and outcomes that are related to the implementation of environmental management system (EMS) models. The findings indicate that “market benefits and cost reduction are the key drivers of the Eco-lighthouse, while customer pressure and improved environmental routines pull ISO 14001 certification. A higher level of customer pressure for environmental management system favours ISO 14001 adoption over Eco-Lighthouse adoption. While Eco-Lighthouse certification is challenged by a low realisation of market benefits, the challenges that relate to employee buy-in, competence and time are more prominent for ISO 14001 adoption. While similar sustainability practices were identified within all of the studied companies, the ISO 14001 certified companies were more systematic and formal in their identification and management of environmental improvements."[263]

Cote et al. (2008) confirmed that "time and, to a lesser degree, financial resources to address solid waste and energy issues are the greatest limiting factors. Small suppliers, and even to a certain degree medium-sized enterprises, have difficulties in allocating resources to initiatives that are not viewed as directly related to their core function, namely manufacturing the product or providing the service."[264] The study demonstrated that "opportunities exist to reduce greenhouse gas emissions and solid waste. Although, the benefits that would be gained from the implementation of any of the individual actions in the supply chains explored in this study are individually small, the cumulative benefits that could be achieved among supply chains and within industrial parks are substantial, given the number of small- and medium-sized enterprises."[265] According to Vezzoli et al. (2015), "several other articles highlight the importance of local authorities, in developing Sustainable Product Service Systems enabling policies as well as supporting novel networks of stakeholders in the co-production of value"[266] .

Bi et al. (2015) argue that finding the ways to reuse manufacturing resources could bring significant competitiveness to an SME. "Sophisticated machines and tools, such as robots, can be highly utilized even in a manufacturing environment with low or medium product volumes. The concepts of modularization and redesigning, reusing, remanufacturing, recovering, recycling and reducing (6R) processes can be synergized to achieve this goal"[267] (Bi et al, 2015).

Lifecycle assessment

The applications of life cycle assessment (LCA) come in "different forms such as impact assessment, selection, classification and decision support."[268] Chang, Lee and Chen examine the issues or challenges with respect to the four steps of LCA, that is, goal and scope definition, life cycle inventory, life cycle impact analysis and interpretation (Chang et al, 2014).

---

[263] Granly, BM; Webo, T. 2014. EMS and sustainability: experiences with ISO 14001 and Eco-Lighthouse in Norwegian metal processing SMEs. J. Clean Prod., vol. 64, FEB 1, page 194 [62]

[264] Cote, RP; Lopez, J; Marche, S; Perron, GM; Wright, R. 2008. Influences, practices and opportunities for environmental supply chain management in Nova Scotia SMEs. J. Clean Prod., vol. 16, 15, page 1561 [29]

[265] ibidem

[266] Vezzoli, C; Ceschin, F; Diehl, JC; Kohtala, C. 2015. New design challenges to widely im-plement 'Sustainable Product-Service Systems'. J. Clean Prod., vol. 97, JUN 15, page 1 [146]

[267] Bi, ZM; Liu, YF; Baumgartner, B; Culver, E; Sorokin, JN; Peters, A; Cox, B; Hunnicutt, J; Yurek, J; O'Shaughnessey, S. 2015. Reusing industrial robots to achieve sustainability in small and medium-sized enterprises (SMEs). Ind. Robot, vol. 42, 3, page 264 [5]

[268] Chang, DN; Lee, CKM; Chen, CH. 2014. Review of life cycle assessment towards sustainable product development. J. Clean Prod., vol. 83, NOV 15, page 48 [17]

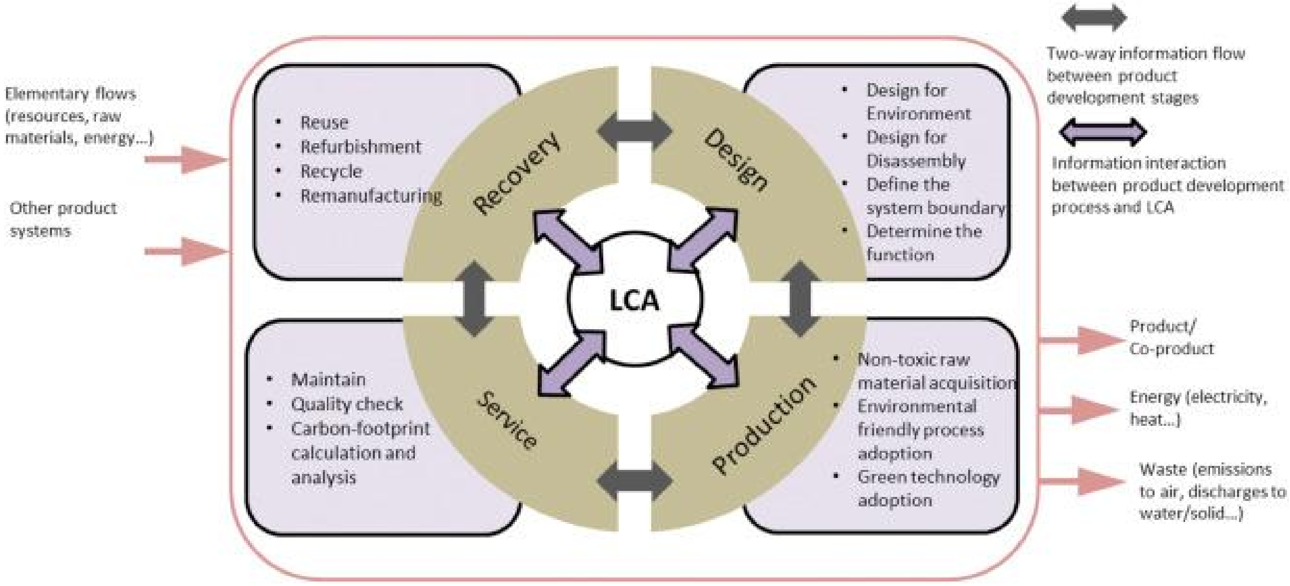


Figure 3. Interrelated strands of product development for the LCA[269] (source: Chang et al, 2014)

Ruhnau and Bunzel (2014) provide "an overview of potential ways of how to set prices for certain technologies, features and specifications for passenger cars focusing on the original equipment manufacture's (OEM's) view."[270] "Pricing sustainable features is also possible if the OEM acts as the first mover on the condition that the feature which is intended to be priced is not linked to a matter of legislation. If it is a matter of legislation, but giving a pricing signal to competitors is possible, assigning a price to the feature is still feasible."[271] In the pricing process, "the first step to find the optimum price position for a sustainable feature is to set price boarders."[272]

Ruhnau and Bunzel (2014) present "a set of suitable ways to reflect the corporate strategy, competition, characteristics of the feature to be priced, market and communication within the pricing process."[273] "Availability as well as functionality and price have an indirect influence on brand experience and therefore brand value, which leads to higher achievable prices and/or volumes. In most cases, this effect is not quantifiable. In the best case one can measure brand values at customer surveys but a valid link to pricing is hard to establish. If general standards and communication aspects are in place (e.g. CO_2 emissions and fuel consumption with col-

[269] Chang, DN; Lee, CKM; Chen, CH. 2014. Review of life cycle assessment towards sustainable product development. J. Clean Prod., vol. 83, NOV 15, page 58 [17]

[270] Ruhnau, T; Bunzel, WM. 2014. Sustainability in Automotive Pricing. SUSTAINABLE AUTOMOTIVE TECHNOLOGIES 2013, SEP 25–27, 2013, page 143 [121]

[271] Ibidem.

[272] Ibidem.

[273] Ibidem.

oured efficiency class “B”) customer’s awareness is much more likely to follow than in cases where information about technologies is hidden.”[274] Ruhnau and Bunzel (2014) “sharpen the view on different ways to offer sustainable features by presenting two examples from practice.”[275]

3.1.2 Energy efficiency

Salonitis and Ball (2013) present “an overview of energy efficiency approaches, focusing in both production and machine tool level and how these two can be integrated together. Furthermore, the main challenges towards energy efficient manufacturing are discussed identifying the major barriers from both technology and cultural point of view.”[276] The discussion here follows Sorrell et al. (2000) who categorized these barriers into three major groups: Economic barriers, Behavioural barriers and Organizational barriers.

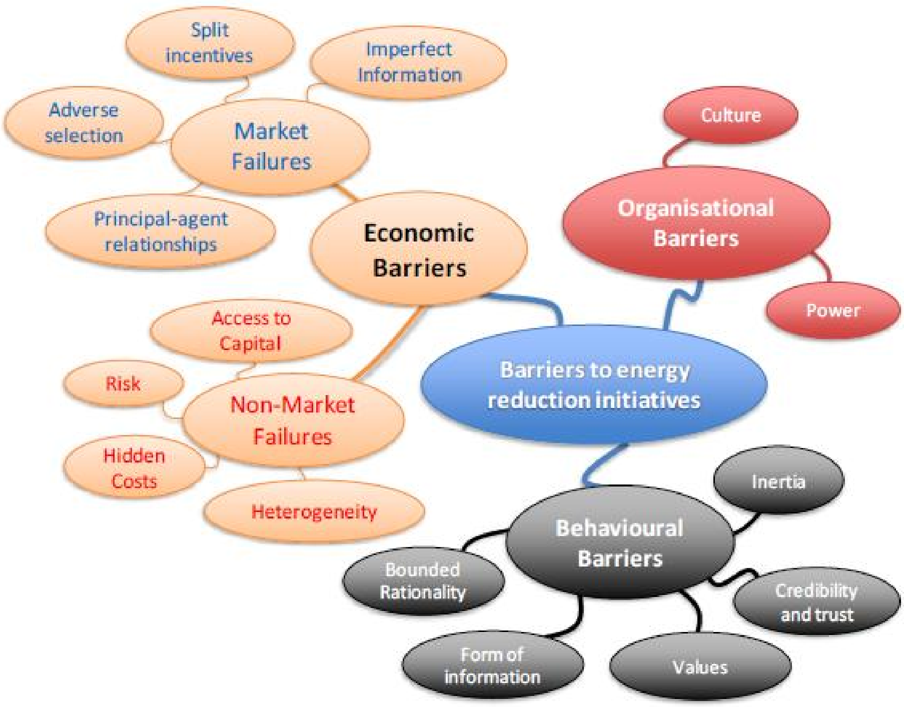


Figure 4. Barriers to energy reduction (source: Sorrell et al, 2000[277])

---

[274] Ruhnau, T; Bunzel, WM. 2014. Sustainability in Automotive Pricing. SUSTAINABLE AUTOMOTIVE TECHNOLOGIES 2013, SEP 25–27, 2013, page 148 – 149 [121]

[275] ibidem , page 143 [121]

[276] Salonitis, K; Ball, P. 2013. Energy efficient manufacturing from machine tools to manu-facturing systems. FORTY SIXTH CIRP CONFERENCE ON MANUFACTURING SYSTEMS 2013, MAY 29–30, 2013, page 634 [122]

[277] Sorrell, S.; Schleich, J.; Scott, S.; O’Malley, E.; Trace, F.; Boede, U.; Ostertag, K. and Radgen, P. 2000. Reducing barriers to energy efficiency in public and private organiza-tions, SPRU, page 59 [135]

The photovoltaic (PV) industry has grown very rapidly during the last few years. “Since 2008, the average manufacturer-sale price of PV modules has declined by more than a factor of two, coinciding with a significant increase in the scale of manufacturing in China.”[278] Goodrich et al. (2013) “quantify the conditions of China’s historical PV price advantage, examine whether these conditions can be reproduced elsewhere, and evaluate the role of innovative technology in altering regional competitive advantage.”[279] Goodrich et al. (2013) find that “the historical price advantage of a China-based factory relative to a US-based factory is not driven by country-specific advantages, but instead by scale and supply-chain development.”[280] The findings “highlight the role of innovation, importance of manufacturing scale, and opportunity for global collaboration to increase the installed capacity of PV worldwide.”[281]

According to Gestlberger, Knudsen and Stampe (2014), very few studies has focused on the interaction between product innovation and companies’ activities aimed at improving the energy efficiency of production facilities. Utilizing the 2009 European Manufacturing Survey for the Danish sub-sample including 335 manufacturing firms, the authors confirm “three main areas of focus of new product development: efficiency considerations, market attention, and greening of innovation.”[282] The analysis demonstrates that, “while market attention is important for the development of new products, green aspects of innovation and efficiency considerations are important for production companies wanting to improve their energy efficiency. When these models are combined, the results highlight that energy efficiency moderates the effect of market attention to new product development.”[283] Gerstlberger, Knudsen and Stampe (2014) therefore find that “aligning product innovation and energy efficiency is a complex and intertwined process – focusing on one may have indirect detrimental effects on the other. These results point to the conclusion that researchers and practitioners in innovation management have to more carefully consider the specificities and interactions of different types of products and process innovations and their environmental implications, and must formulate new, more sustainable managerial practices combining energy efficiency and product innovation.”[284]

---

[278] Goodrich, AC; Powell, DM; James, TL; Woodhouse, M; Buonassisi, T. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci., vol. 6, OCT, page 2811 [59]

[279] Ibidem.

[280] Ibidem.

[281] Ibidem.

[282] Goodrich, AC; Powell, DM; James, TL; Woodhouse, M; Buonassisi, T. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci., vol. 6, OCT, page 2811 [59]

[283] Ibidem.

[284] Ibidem.

3.1.3 Biomanufacturing & sustainable nanotechnology

Nanotechnology is currently integrating chemistry and materials science, and in some cases integrating these with biology so as to create new and value adding properties that can be exploited in order to gain new market opportunities. Zhao, Boxman and Chowdhry (2003) present "market opportunities for nanotechnology from an industrial perspective covering electronic, biomedical, performance materials, and consumer products." [285]

Figure 5 "describes a nanotechnology innovation pathway that incorporates models using both technology-push and market-pull. Nanoparticles or nanostructures provide the building blocks for product design. Process understanding aims to improve efficiency for optimal manufacturing process design. Product design is aimed at matching product functionality to customer needs, and value chain understanding will assist optimization of each step from materials producer to end-use customer. Thinking through the best way to design each step in this pathway is essential for the field of nanotechnology to achieve its anticipated promise"[286] (Zhao et al, 2003). As an example, Misson, Zhang and Jin (2015) demonstrated a great potential of nanobiocatalysts in manufacturing bioprocesses in the near future through successful laboratory trials of nanobiocatalysts in carbohydrate hydrolysis, biofuel production and biotransformation.

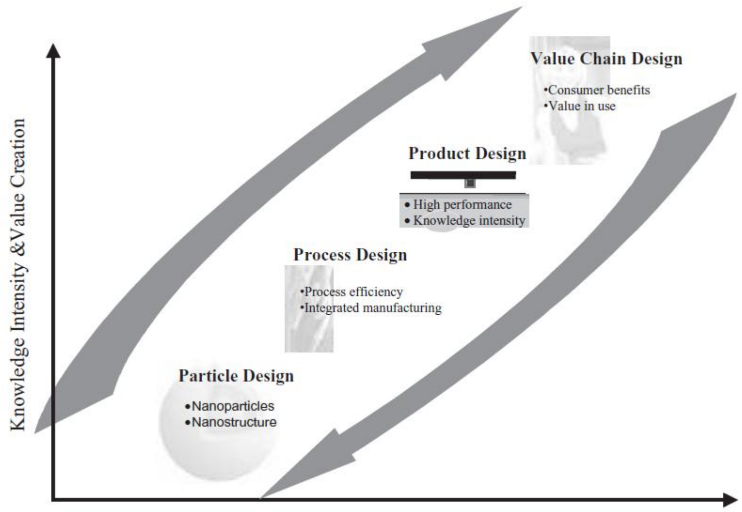


Figure 5. Nanotechnology innovation roadmap (source: Zhao et al, 2003[287])

[285] Zhao, QQ; Boxman, A; Chowdhry, U. 2003. Nanotechnology in the chemical industry – opportunities and challenges. J. Nanopart. Res., vol. 5, DEC, page 567 [160]

[286] Zhao, QQ; Boxman, A; Chowdhry, U. 2003. Nanotechnology in the chemical industry – opportunities and challenges. J. Nanopart. Res., vol. 5, DEC, page 572 [160]

[287] Ibidem, page 572 [160]

The unique advantage of nanotechnology is due to nanoscale physical and chemical properties that are quite different from those encountered in microscopic or macroscopic materials and devices. Unique nanoscale properties and behaviours are already being used so as to increase energy efficiency, improve healthcare, and strengthen national security (Romig, 2004).

Indeed, investments in nanomaterials, nanofabrication and nanometrology have provided the R&D community with a vast array of new technologies. These technologies promise radical change in traditional industries, such as transportation, information and aerospace, but may create whole new industries also, such as personalized medicine and personalized energy harvesting and storage. However, one challenge today is determining how to accelerate the conversion of these technical opportunities into concrete benefits with quantifiable impact. Moreover, there are still outstanding scientific questions that are limiting their utilization. For example, "nanomaterial fabrication delivers substantial tailorability beyond a traditional material data sheet. How can we integrate this tailorability into agile manufacturing and design methods to further optimize the performance, cost and durability? The intersection of nano-based metamaterials and nanostructured devices with biotechnology epitomizes the technological promise of autonomous systems and enhanced human-machine interfaces."[288] Vaia (2012) then asks what the key materials and processes challenges are that "are inhibiting current lab-scale innovation from being integrated into functioning systems to increase the effectiveness and productivity of our human resources."[289]

3.2 Organizational Context

3.2.1 Sustainability in manufacturing

From design to disposal and reuse

Recycling of waste electrical and electronic equipment (WEEE) is an important subject not only from the viewpoint of waste treatment, but also from the viewpoint of recovery of valuable materials. There are a number of obstacles that make recycling challenging for today's manufactured products. "First, it is difficult to gain all the information necessary to plan for the recycling evaluation, as most design information is owned and kept by suppliers. Another problem in recycling end-of-life (EOL) products is a lack of technologies to handle the very complex

---

[288] Vaia, RA. 2012. Nanomaterials and Future Aerospace Technologies: Opportunities and Challenges. MICRO- AND NANOTECHNOLOGY SENSORS, SYSTEMS, AND APPLICATIONS IV, APR 23–27, 2012, page 837324-1 [144]

[289] Ibidem.

products that are being discarded today, because the knowledge of how to do so is owned by the recycler”[290] (Tsai, 2010).

Salvador et al. (2014) have found that although configuring of products to individual customer orders is common in many industries, little is known about the capabilities that firms need when offering configurable products. Moreover, a great challenge facing industry today is managing variety throughout the entire product life cycle. ElMaraghy et al. (2013) present “drivers of products variety, its benefits, pre-requisites and associated complexity and cost.”[291] They discuss “enhancing consumers’ value through variety and approaches to achieving it efficiently including modularity, commonality and differentiation.”[292] ElMaraghy et al. (2013) review variant-oriented manufacturing systems paradigms, as enablers of product variety, and the effective co-development of variants and their manufacturing systems to ensure economic sustainability. They also discuss industrial applications and guidelines to achieve economy of scope with advantages of economy of scale. Salvador, Chandrasekaran and Sohail (2014) argue that “firms have to balance the dual goals of reducing variation and promoting variation in their product configuration activities by fostering two distinct firm-level capabilities: product configuration effectiveness (PCE) and product configuration intelligence (PCI)”[293].

The development of ecodesign is dedicated to improving a product’s environmental performance, throughout its life cycle. Li, Zeng and Stevels (2015) expand the theory and application of ecodesign, “owing largely to the development of more environmentally friendly materials, newly emerging technology, and legislation mandating better handling of consumer electronics – both in manufacturing and in waste treatment. Yet many challenges and opportunities remain, including the pressure that the huge consumer electronics market exerts on resources; new materials and technology such as carbon nanomaterial and the Internet of Things; the need to balance business profit with environmental impacts and benefits; and a significant shift of focus in the processing of electronic waste-from dismantling for recycling to disassembly for remanufacturing.”[294]

Kuo (2010) demonstrates “how to support WEEE recycling analysis by environmental information with the part of Bill-of-Material. A collaborative-design platform is further constructed and collected all the necessary information using computer-aided design (CAD), enterprise

[290] Tsai, CK. 2010. The construction of a collaborative-design platform to support waste electrical and electronic equipment recycling. Robotics and Computer-Integrated Manufacturing 26(1), February, page 100 [141]

[291] ElMaraghy, H; Schuh, G; ElMaraghy, W; Piller, F; Schonsleben, P; Tseng, M; Bernard, A. 2013. Product variety management. CIRP Ann-Manuf. Technol., vol. 62, 2, page 629 [37]

[292] ibidem

[293] ibidem

[294] Li, JH; Zeng, XL; Stevels, A. 2015. Ecodesign in Consumer Electronics: Past, Present, and Future. Crit. Rev. Environ. Sci. Technol., vol. 45, APR 18, page 840 [86]

resource planning (ERP), and product life-cycle management (PLM) systems. Through this platform, suppliers are required to provide component information to enable the manufacturer's design for disassembly and recycling analysis."[295]

Managing product lifecycle

Lifecycle assessment (LCA)-based analyses of value chains can propose profound modifications to product design, and to all the different phases throughout the lifecycle of the product including, manufacturing, distribution, use, and disposal. Such modifications often create tradeoffs; they improve some aspects while worsen others. It will be difficult to decide whether or not to carry out such modifications. Or prioritize between different options to choose the one delivering the most competitive advantage. "Typically, firms' metrics fall into two groups: (1) product-level metrics across the life cycle, including up-and downstream of facilities (e.g., product carbon footprints), and (2) facility-level metrics (e.g., plants' annual energy cost). Neither is sufficient for firm-wide cost-benefit analyses of modifications that affect multiple products and value-chain stages. Whereas facility-level metrics do not capture up-and downstream effects, where often most cost and environmental impacts originate, life cycle methodologies are currently not mature enough to be applied at the scale of entire product portfolios" [296] (Meinrenken et al, 2014).

Information technology (IT) "presents opportunities for firms to greening IT and/or increasing their efficiency of resource use."[297] Wang, Chen and Benitez-Amado (2015) find that: "(1) Firm's proficiency in leveraging IT technical infrastructure flexibility, IT personnel skills and IT-business alignment enables the integration of IT in the environmental management processes to improve environmental performance, and (2) this IT integration is stronger when the firm is more oriented to environmental sustainability."[298]

Having sustainability and environmental impact as design drivers calls for integrated methods for part design and product development. Only then, "any benefits of sustainable composite material systems can be assessed during the design process. These methods must include mechanisms to account for process induced part variation and techniques related to re-

[295] Kuo, TC. 2010. The construction of a collaborative-design platform to support waste electrical and electronic equipment recycling. Robot. Comput.-Integr. Manuf., vol. 26, FEB, page 100 [82]

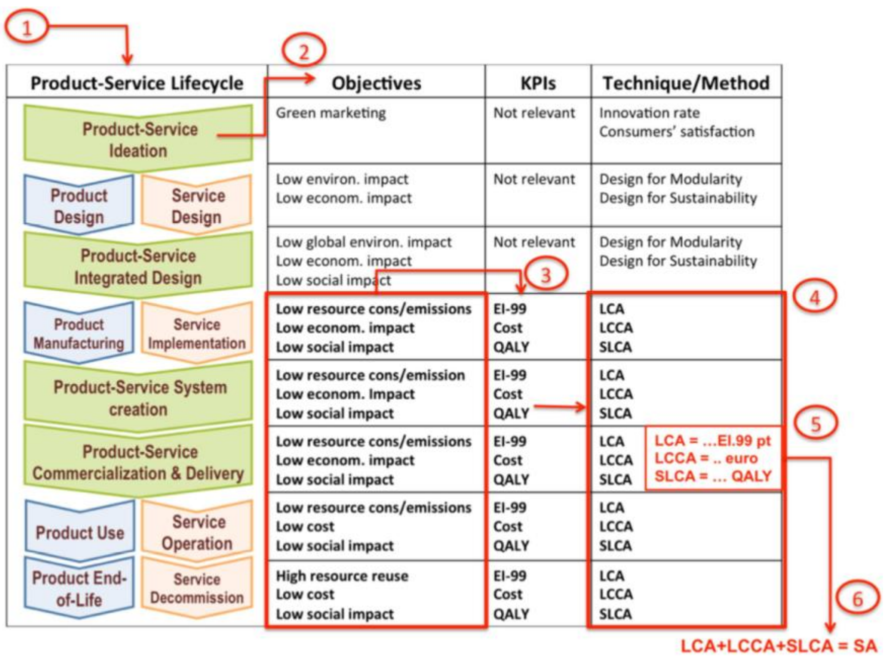
[296] Meinrenken, CJ; Sauerhaft, BC; Garvan, AN; Lackner, KS. 2014. Combining Life Cycle Assessment with Data Science to Inform Portfolio-Level Value-Chain Engineering A Case Study at PepsiCo Inc. J. Ind. Ecol., vol. 18, OCT, page 641 [99]

[297] Wang, Y; Chen, Y; Benitez-Amado, J. 2015. How information technology influences environmental performance: Empirical evidence from China. Int. J. Inf. Manage., vol. 35, APR, page 160 [150]

[298] Ibidem

forming, recycling and decommissioning, which are in their infancy."[299] McEwan and Butterfield (2011) propose that "predictive techniques related to material specification, part processing and product cost of thermoplastic composite components, be integrated within a Through Life Management (TLM) product development methodology as part of a larger strategy of product system modelling to improve disciplinary concurrency, realistic part performance, and to place sustainability at the heart of the design process."[300]

Peruzzini, Germani and Marilungo (2013) define "an integrated product-service lifecycle and propose a methodology to identify a set of KPIs for both Product Service Systems (PSS) and products and to compare different use scenarios."[301] It "adopts a holistic approach to assess sustainability on the basis of the three main impacts: environmental, economic and social. The methodology is illustrated by means of an industrial case study focusing on water heaters; it analyses an innovative PSS "Hot water as a Service" supported by an extended network, and compares it with the traditional scenario based on product selling supported by a vertical supply-chain."[302]



---

[299] McEwan, W; Butterfield, J. 2011. A Digital Methodology for the Design Process of Ae-rospace Assemblies with Sustainable Composite Processes & Manufacture. 14TH INTERNATIONAL CONFERENCE ON MATERIAL FORMING ESAFORM, 2011 PROCEEDINGS, APR 27–29, 2011, page 1683 [97]

[300] McEwan, W; Butterfield, J. 2011. A Digital Methodology for the Design Process of Ae-rospace Assemblies with Sustainable Composite Processes & Manufacture. 14TH INTERNATIONAL CONFERENCE ON MATERIAL FORMING ESAFORM, 2011 PROCEEDINGS, APR 27–29, 2011, page 1683 [97]

[301] Peruzzini, M; Germani, M; Marilungo, E. 2013. Design for sustainability of product-service systems in the extended enterprise. 20TH ISPE INTERNATIONAL CONFERENCE ON CONCURRENT ENGINEERING, SEP 02–06, 2013, page 314 [110]

[302] Ibidem

Figure 6. Methodology for Product-Service sustainability assessment (source: Peruzzini et al, 2013[303])

McEwan and Butterfield (2011) report "the enhancement of digital manufacturing tools as a means of drawing simulated part manufacturing scenarios, real time costing mechanisms, and broader lifecycle performance data capture into the design cycle. The work demonstrates predictive processes for sustainable composite product manufacture and how a Product – Process – Resource (PPR) structure can be customised and enhanced to include design intent driven by part geometry and consequent assembly."[304]

3.2.2 Energy efficiency

Modern manufacturing supply chains are often complex and long. They lead to significant barriers to the measurement and minimization of energy consumption and therefore to barriers to the implementation of sustainable manufacturing. Baumers et al. (2013) "investigate whether the adoption of additive manufacturing (AM) technology can be used to provide transparency in terms of energy and financial inputs to manufacturing operations."[305] "The parallel character of AM (allowing the contemporaneous production of multiple parts) poses previously unconsidered questions in the estimation of manufacturing resource consumption."[306] Baumers et al. (2013) discuss "the implementation of a tool for the estimation of process energy flows and costs occurring in the AM technology variant direct metal laser sintering. It is demonstrated that accurate predictions can be made for the production of a basket of sample parts. Furthermore, it is shown that the quantity and variety of parts demanded and the resulting ability to fully utilize the available machine capacity have an impact on process efficiency. It is also demonstrated that cost minimization in additive manufacturing may lead to the minimization of process energy consumption, thereby motivating sustainability improvements."[307]

Shrouf and Miragliotta (2015) expect "the Internet of Things paradigm to increase the visibility and awareness of energy consumption."[308] They say that "real-time energy consumption data from manufacturing processes can easily be collected, and then analysed, to improve energy-

[303] Ibidem, page 318 [110]

[304] McEwan, W; Butterfield, J. 2011. A Digital Methodology for the Design Process of Ae-rospace Assemblies with Sustainable Composite Processes & Manufacture. 14TH INTERNATIONAL CONFERENCE ON MATERIAL FORMING ESAFORM, 2011 PROCEEDINGS, APR 27–29, 2011, page 1683 [97]

[305] Baumers, M; Tuck, C; Wildman, R; Ashcroft, I; Rosamond, E; Hague, R. 2013. Transpa-rency Built-in Energy Consumption and Cost Estimation for Additive Manufacturing. J. Ind. Ecol., vol. 17, JUN, page 418 [3]

[306] ibidem, page 418 [3]

[307] ibidem, page 418 [3]

[308] Shrouf, F; Miragliotta, G. 2015. Energy management based on Internet of Things: prac-tices and framework for adoption in production management. J. Clean Prod., vol. 100, AUG 1, page 235 [129]

aware decision-making."[309] Based on a literature review and on experts' insights, Shrouf and Miragliotta (2015) contribute to "the understanding of energy-efficient production management practices that are enhanced and enabled by the Internet of Things technology. In addition, it discusses the benefits that can be obtained thanks to adopting such management practices."[310]

3.2.3 Biomanufacturing & sustainable nanotechnology

More and more researchers are interested in continuous processing in biologics manufacturing. "The advantages of continuous manufacturing include sustained operation with consistent product quality, reduced equipment size, high-volumetric productivity, streamlined process flow, low-process cycle times, and reduced capital and operating cost. This technology, however, poses challenges, which need to be addressed before routine implementation is considered."[311] Based on the available literature and input from a large number of reviewers, Konstantinov and Cooney (2015) provide "a consensus of the opportunities, technical needs, and strategic directions for continuous bioprocessing. The discussion is supported by several examples illustrating various architectures of continuous bioprocessing systems."[312]

Social implications of nanotechnology

Designing on a nanoscale allows for redesign of the structure of all materials and for rethinking the possibilities for use of any and all materials. Such changes will introduce tremendous social and ethical issues. "The ethical and social implications of nanotechnology encompass many key areas associated with development, such as privacy, security, the environment, and food and agriculture."[313] Khan (2014) presents "an overview of new and emerging nanotechnologies and applications and their ethical and social implications in addressing 21st century challenges and issues."[314]

Also, Engeman et al. (2013) point out that "the potential adverse human health effects of manufactured nanomaterial exposure are not yet fully understood, and exposures in humans are mostly uncharacterized. Appropriate exposure control strategies to protect workers are still being developed and evaluated, and regulatory approaches rely largely on industry self-

---

309 Ibidem

310 Shrouf, F; Miragliotta, G. 2015. Energy management based on Internet of Things: prac-tices and framework for adoption in production management. J. Clean Prod., vol. 100, AUG 1, page 235 [129]

311 Konstantinov, KB; Cooney, CL. 2015. White Paper on Continuous Bioprocessing May 20–21, 2014 Continuous Manufacturing Symposium. J. Pharm. Sci., vol. 104, MAR, page 813 [80]

312 Ibidem.

313 Khan, AS. 2014. Ethics and Nanotechnology. 2014 IEEE INTERNATIONAL SYMPOSIUM ON ETHICS IN SCIENCE, TECHNOLOGY AND ENGINEERING, MAY 23–24, 2014, page 1 [76]

314 Ibidem.

regulation and self-reporting."[315] In this context of soft regulation, Engeman et al. (2013) sought to: "1) assess current company-reported environmental health and safety practices in the United States throughout the product life cycle, 2) consider their implications for the manufactured nanomaterial workforce, and 3) identify the needs of manufactured nanomaterial companies in developing nano-protective environmental health and safety practices."[316]

Process development

The application of state-of-the-art process systems engineering technologies is limited for small scale processes. "The limitation due to the cost-benefit ratio is particularly high when attempting to optimise process operation, in comparison with process design topics. There is an enormous potential for process systems engineering in the life science area though, since a larger number of smaller improvements is resulting in an enormous economic impact"[317] (Dunnebier, 2008).

SixSigma is a methodology for process improvements. "Originating from American manufacturing industries with a strong focus on statistical methods," it "identifies causes for (operational) problems based on statistical data and economic drivers."[318] Dunnebier (2008) discusses "the special requirements of process industries and some useful extensions of the Six Sigma toolbox and also shows how the identification and prioritisation of problems leads to the application of CAPE tools in areas where otherwise the hurdle for their application would have been too high. This is being illustrated using an industrial example from a biotechnological production of pharmaceutical, where the original project scope to stabilise product yield and impurities led to applying advanced control, dynamic simulation and dynamic optimisation in addition to the "low hanging fruits" being related to, e.g., improvements of manual process steps."[319]

---

[315] Engeman, CD; Baumgartner, L; Carr, BM; Fish, AM; Meyerhofer, JD; Satterfield, TA; Holden, PA; Harthorn, BH. 2013. The Hierarchy of Environmental Health and Safety Practices in the US Nanotechnology Workplace. J. Occup. Environ. Hyg., vol. 10, SEP 1, page 487 [39]

[316] Engeman, CD; Baumgartner, L; Carr, BM; Fish, AM; Meyerhofer, JD; Satterfield, TA; Holden, PA; Harthorn, BH. 2013. The Hierarchy of Environmental Health and Safety Practices in the US Nanotechnology Workplace. J. Occup. Environ. Hyg., vol. 10, SEP 1, page 487 [39]

[317] Dunnebier, G. 2008. Troubleshooting and process optimisation by integrating CAPE tools and Six Sigma methodology. 18TH EUROPEAN SYMPOSIUM ON COMPUTER AIDED PROCESS ENGINEERING, JUN 01–04, 2008, page 943 [35]

[318] Ibidem.

[319] Ibidem.

3.3 Technological Context

3.3.1 Sustainability in manufacturing

Lee, Kang and Noh (2014) introduce "MAS(2), which is an integrated modelling and simulation-based life cycle evaluation approach for sustainable manufacturing. Four requirements that are essential for evaluating the sustainability performance of manufacturing industries are suggested. The proposed MAS(2) approach consists of the following main components: 1) a theoretical foundation comprising 20 principles and definitions of sustainable manufacturing and manufacturing sustainability, 2) indicators, namely the MAS(2) indicator and Manufacturing Sustainability Index (MSI), 3) e-MAS(2) as an evaluation method, and 4) i-MAS(2) as an information management method."[320]

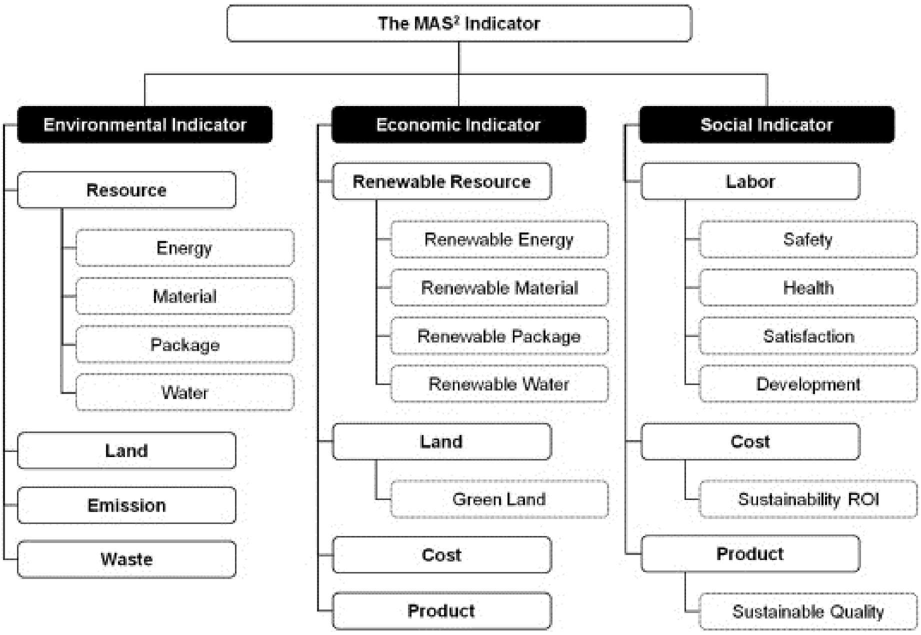


Figure 7. The MAS(2) indicator (source: Lee et al, 2014[321])

Meinrenken et al. (2014) present "a pilot system of key performance indicators (KPIs) that evaluate 3,337 products across 211 brands and five countries of PepsiCo, Inc. KPIs are firm-wide, annual figures (environmental, operational, and financial) across the value chain (cradle to grave) and can be determined at any level (single product, brands, or regions). Uncertainty analysis is included. In addition to KPIs for base cases, the system characterizes KPI impacts for

---

[320] Lee, JY; Kang, HS; Noh, SD. 2014. MAS(2): an integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing. J. Clean Prod., vol. 66, Nov 1, page 146 [84]

[321] Lee, JY; Kang, HS; Noh, SD. 2014. MAS(2): an integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing. J. Clean Prod., vol. 66, Nov 1, page 150 [84]

any considered modifications (what-if scenarios)."[322] "As a result, environmental impacts can be considered on a routine basis as part of integrated strategy and business planning."[323] Meinrenken et al. (2014) discuss implementation considerations of the KPI methodology and future improvements also.

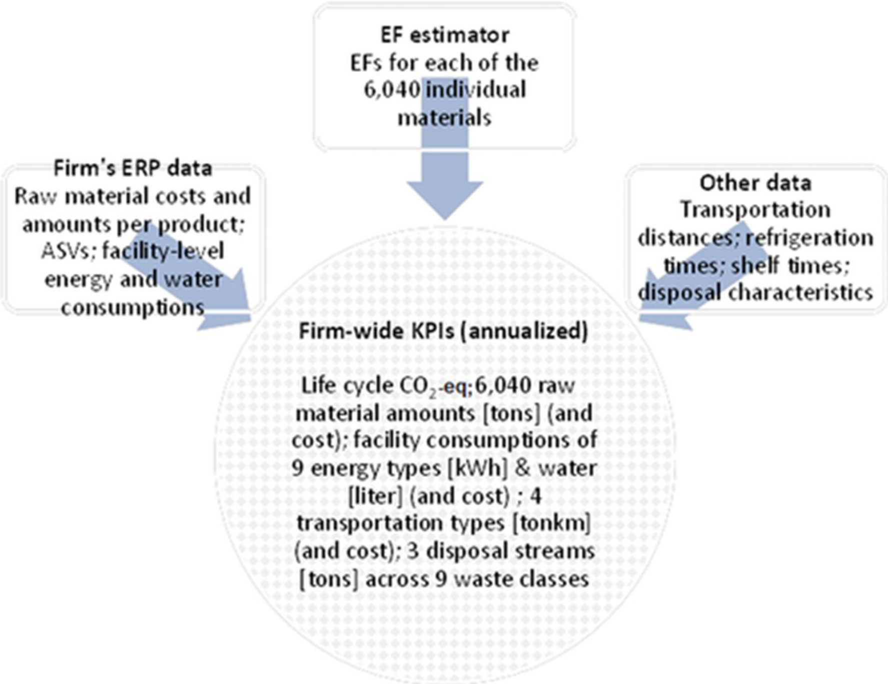


Figure 8. Combining Life Cycle Assessment with Data Science to Inform Portfolio-Level Value-Chain Engineering (source: Meinrenken et al, 2014[324])[325]

Kalla et al. (2012) focus "on two issues that must be addressed to ensure continued growth in fibre-reinforced polymer (FRP) usage is the disposal of waste generated during product manufacturing and the disposal of the products at the end of their useful life. The major cost drivers for FRPs are labour and raw materials. The use of recycled FRPs offers low-cost raw materials."[326] Kalla et al. (2012) present a review of the current status and outlook of fibre-reinforced

---

[322] Meinrenken, CJ; Sauerhaft, BC; Garvan, AN; Lackner, KS. 2014. Combining Life Cycle Assessment with Data Science to Inform Portfolio-Level Value-Chain Engineering A Case Study at PepsiCo Inc. J. Ind. Ecol., vol. 18, OCT, page 641 [99]

[323] Ibidem.

[324] Meinrenken, CJ; Sauerhaft, BC; Garvan, AN; Lackner, KS. 2014. Combining Life Cycle Assessment with Data Science to Inform Portfolio-Level Value-Chain Engineering A Case Study at PepsiCo Inc. J. Ind. Ecol., vol. 18, OCT, page 646 [99]

[325] ERP = enterprise resource planning; ASV = annual sales volumes; EF = emission factor; KPI = key performance indicator; CO2-eq = carbon dioxide equivalents; kWh = kilowatt-hour

[326] Kalla, DK; Dhanasekaran, PS; Zhang, BW; Asmatulu, R. 2012. SUSTAINABILITY OF FIBER REINFORCED COMPOSITES: STATUS AND VISION FOR FUTURE. PROCEEDINGS OF THE ASME INTERNATIONAL MECHANICAL ENGINEERING CONGRESS AND EXPOSITION 2011, VOL 3, NOV 11–17, 2011, page 167 [75]

polymer composites recycling and re-manufacturing techniques. They also "state the sustainability problems of fibre-reinforced composite products, and potential solutions."[327]

"Inability to compare additive manufacturing (AM) performance against traditional manufacturing methods can be a barrier to implementing AM processes. AM process sustainability has become a driver due to growing environmental concerns for manufacturing. This has reinforced the importance of understanding and characterizing AM processes for sustainability." [328] Mani, Lyons and Gupta (2014) examine the potential environmental impacts of AM. "A methodology for sustainability characterization of AM is then proposed to serve as a resource for the community to benchmark AM processes for sustainability."[329]

3.3.2 Energy efficiency

In his study, Cipollone (2013) concludes that "the most important energy saving measures are associated with the: (1) reduction of leakages on the distribution lines, (2) a more appropriate compressed air system design, (3) use of adjustable speed drives, (4) waste heat recovery. All these aspects, in a ten-year period of operation, weigh 70–75 % of the overall compressed air costs compressor technology is, therefore, a key factor to reduce energy consumption including in it load control, variable speed operation, compressor sizing, etc. A great potential saving is associated with leaks, friction pipes, etc., but these actions are downstream of the compressed air production"[330] (Cipollone, 2013).

"Compressed air is produced by electrical energy, and the consumption accounts as much as 10 % of industrial consumption of electricity. A lower estimate places at 6 % this share but an additional 12 % is estimated to be associated with the commercial and residential markets (portable tools, air pumps, pneumatic heating, ventilation, air conditioning, etc.), so overall compressor needs are estimated to be equal to 20 % of the industrial electricity needs. Considering that industrial consumption of electricity represents a given share of the overall electrical energy consumption (it depends on the geographical context, social development, industrial level, etc.), with a good approximation, compressed air can be associated with the overall electricity consumption and to primary energy consumption too"[331] (Cipollone, 2013).

Power monitoring is necessary for the quantification of energy efficiency. It helps to limit the expensive peak power use and control the process stability. However, the monitoring of high-

---

[327] Ibidem

[328] Mani, M; Lyons, KW; Gupta, SK. 2014. Sustainability Characterization for Additive Ma-nufacturing. J. Res. Natl. Inst. Stand. Technol., vol. 119, SEP 22, page 419 [96]

[329] Ibidem

[330] Cipollone, R. 2013. Sliding vane rotary compressor technology and energy saving. 8TH INTERNATIONAL CONFERENCE ON COMPRESSORS AND THEIR SYSTEMS, SEP 09–10, 2013, page 27 [24]

[331] ibidem

performance processes can be challenging. Humphrey et al. (2014) provide "a basic introduction into power and energy measurement for three phase power and discuss the advantages of high-frequency power monitoring. These include ease of generation (three phase electric transformers are considerably cheaper to build than single phase transformers of comparable power.), ease of transmission and ease of electric motor design" [332] (Humphrey et al, 2014).

However, "ad hoc power measurement in industrial settings is often complicated by comparatively trivial obstacles and is, thus, often less simple to perform than the theoretical fundamentals might lead one to expect. Wiring plans for machines sometimes do not reflect changes applied after installation or might be missing altogether. While some commercially available power measurement devices feature wiring diagnostic checks, these do not always produce accurate results. Matters are often further complicated by the fact that cable colouring varies by country and sometimes even by time period. For comprehensive power monitoring, power meters can also be integrated into existing machines. Since commercially available power measurement devices used for ad hoc power measurement are often expensive, cheap, reliable embedded solutions are required. Aside from cost and reliability aspects embedded solutions for interconnected industry must be accessible and secure"[333] (Humphrey et al, 2014).

3.3.3 Biomanufacturing & sustainable nanotechnology

Biofibres and biocomposites

Natural fibres are used more and more in composite manufacturing. "Biofibres such as plant fibres are replacing synthetic fibres in composites,"[334] since they provide sustainability benefits (Ramamoorthy et al, 2015). "Natural fibres possess a high strength to weight ratio, non-corrosive nature, high fracture toughness, renewability, and sustainability, which give them unique advantages over other materials" [335] (Namvar et al, 2014).

"The development of biocomposites by reinforcing natural fibres has attracted the attention of scientists and researchers due to environmental benefits and improved mechanical perfor-

[332] Humphrey, S; Papadopoulos, H; Linke, B; Maiyya, S; Vijayaraghavan, A; Schmitt, R. 2014. Power measurement for sustainable high-performance manufacturing processes. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, page 466 [70]

[333] Humphrey, S; Papadopoulos, H; Linke, B; Maiyya, S; Vijayaraghavan, A; Schmitt, R. 2014. Power measurement for sustainable high-performance manufacturing processes. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, page 469 [70]

[334] Ramamoorthy, SK; Skrifvars, M; Persson, A. 2015. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. Polym. Rev., vol. 55, JAN 2, page 107 [116]

[335] Namvar, F; Jawaid, M; Tahir, PM; Mohamad, R; Azizi, S; Khodavandi, A; Rahman, HS; Nayeri, MD. 2014. Potential Use of Plant Fibres and their Composites for Biomedical Applications. BioResources, vol. 9, 3, page 5688 [102]

mance"[336] (Ramamoorthy et al, 2015). Indeed, "fire-reinforced polymer (FRP) composite products offer many significant environmental benefits such as light weight, superior mechanical properties, extended service life, low maintenance and resistance to corrosion"[337] (Kalla et al, 2014). Plant fibres, particularly bast and leaf, find applications in automotive industries (Ramamoorthy et al, 2015). Similarly, biocomposites are utilized in biomedical applications such as drug/gene delivery, tissue engineering, orthopaedics, and cosmetic orthodontics. "The first essential requirement of materials to be used as biomaterial is its acceptability by the human body. A biomaterial should obtain some important common properties in order to be applied in the human body either for use alone or in combination"[338] (Namvar et al, 2014).

While most of the other fibres are explored on lab scales, they have not yet found large-scale commercial applications. Biocomposites from renewable sources include metals, polymers, and ceramics (Namvar et al, 2014). "It is necessary to also consider other fibers such as ones made from seed (coir) and animals (chicken feather) as they are secondary or made from waste products"[339] (Ramamoorthy et al, 2015). A barrier to the development of different FRP materials has been the difficulty to compare sustainability of these materials and their production processes (Kalla et al, 2012).

Biocompatible nanoparticles

Cellulose is the world's most abundant natural, renewable, biodegradable polymer. Therefore, Postek et al. (2008) argue that the basic raw materials for a future of new nanomaterials breakthroughs are already abound in the environment; they can "be utilized in an array of future materials once the manufacturing processes and nanometrology are fully developed. The use of lignocellulosic fibres derived from sustainable, annually renewable resources as a reinforcing phase in polymeric matrix composites provides positive environmental benefits with respect to ultimate disposability and raw material use."[340] "The basic processes common to manufacturing-qualification of raw materials, continuous synthesis methods, process monitoring and control, in-line and off-line characterization of product for quality control purposes,

---

[336] Ramamoorthy, SK; Skrifvars, M; Persson, A. 2015. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. Polym. Rev., vol. 55, JAN 2, page 107 [116]

[337] Kalla, DK; Dhanasekaran, PS; Zhang, BW; Asmatulu, R. 2012. SUSTAINABILITY OF FIBER REINFORCED COMPOSITES: STATUS AND VISION FOR FUTURE. PROCEEDINGS OF THE ASME INTERNATIONAL MECHANICAL ENGINEERING CONGRESS AND EXPOSITION 2011, VOL 3, NOV 11–17, 2011, page 167 [75]

[338] Namvar, F; Jawaid, M; Tahir, PM; Mohamad, R; Azizi, S; Khodavandi, A; Rahman, HS; Nayeri, MD. 2014. Potential Use of Plant Fibres and their Composites for Biomedical Applications. BioResources, vol. 9, 3, page 5688 [102]

[339] Ramamoorthy, SK; Skrifvars, M; Persson, A. 2015. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. Polym. Rev., vol. 55, JAN 2, page 107 [116]

[340] Postek, MT; Vladar, A; Dagata, J; Farkas, N; Ming, B; Sabo, R; Wegner, TH; Beecher, J. 2008. Cellulose Nanocrystals the Next Big Nano-thing? Instrumentation, Metrology, and Standards for Nanomanufacturing II, AUG 10, 2008, page 70420D-1 [112]

validation by standard reference materials-are not generally in place for nanotechnology based products, and thus are barriers to innovation. One advantage presented is that, unlike other nanomaterials, at least, cellulose nanocrystal manufacturing is already a sustainable and viable bulk process. Literally tons of cellulose nanocrystals can be generated each day, producing other viable by-products such as glucose (for alternative fuel) and gypsum (for buildings). There is an immediate need for the development of the basic manufacturing metrology infrastructure to implement fundamental best practices for manufacturing and in the determination of properties for these for nanoscale materials and the resultant products"[341] (Postek et al, 2008).

In general, while progress is rapid, many challenges remain. These include "manufacturing at the nanoscale, integration of nanoscale materials and devices with more conventional technology, and predictive modelling that will allow nanotechnology to be engineered reliably into useful applications and products"[342] (Romig, 2004). Similarly, Zhao, Boxman and Chowdhry (2003) identify manufacturing technology challenges, including operations ranging from particle formation, coating, dispersion, to characterization, modelling, and simulation.

Nanobiocatalyst (NBC) integrates advanced nanotechnology with biotechnology. It promises advantages for improving enzyme performances in bioprocessing applications. "NBCs are manufactured by immobilizing enzymes with functional nanomaterials as enzyme carriers or containers."[343] Misson, Zhang and Jin (2015) review "the recent developments of novel nanocarriers/nanocontainers with advanced hierarchical porous structures for retaining enzymes, such as nanofibres (NFs), mesoporous nanocarriers and nanocages. Strategies for immobilizing enzymes onto nanocarriers made from polymers, silicas, carbons and metals by physical adsorption, covalent binding, cross-linking or specific ligand spacers are discussed."[344] Misson, Zhang and Jin also highlight several challenges associated with the NBC-driven bioprocess applications, including the maturation of large-scale nanocarrier synthesis, design and development of bioreactors to accommodate NBCs, and long-term operations of NBCs. The authors suggest these challenges are to be addressed through joint collaboration of chemists, engineers and material scientists.

---

[341] Postek, MT; Vladar, A; Dagata, J; Farkas, N; Ming, B; Sabo, R; Wegner, TH; Beecher, J. 2008. Cellulose Nanocrystals the Next Big Nano-thing? Instrumentation, Metrology, and Standards for Nanomanufacturing II, AUG 10, 2008, page 70420D-1 [112]

[342] Romig, AD. 2004. Nanotechnology: Scientific challenges and societal benefits and risks. Metall. Mater. Trans. A-Phys. Metall. Mater. Sci., vol. 35A, DEC, page 3641 [120]

[343] Misson, M; Zhang, H; Jin, B. 2015. Nanobiocatalyst advancements and bioprocessing applications. J. R. Soc. Interface, vol. 12, JAN 6, page 20140891-1 [101]

[344] Ibidem

3D printing

Using three-dimensional (3D) printing techniques you can today produce complex multifunctional structures unimaginable when using conventional manufacturing. Lin et al. (2014) outline "recent progress in materials and manufacturing and propose challenges and opportunities for the future development of 3D printing of functional materials. The success of future 3D printing relies not only on multifunctional materials and printing techniques but also on smart design of complex systems. Engineers need to understand advanced materials, additive manufacturing, and, more importantly, creative design"[345] (Lin et al, 2014).

Titanium, its alloys and several other metals can be used in additive layer manufacturing or metal injection moulding. To some extent these methods can come to replace the machining or casting of metal alloys in the manufacture of devices. This is because of advanced powder manufacturing provides a number of "advantages that include design flexibility, reduced processing costs, reduced waste, and the opportunity to more easily manufacture complex or custom-shaped implants. The emerging advanced manufacturing approaches of metal injection moulding and additive layer manufacturing are receiving particular attention from the implant fabrication industry because they could overcome some of the difficulties associated with traditional implant fabrication techniques such as titanium casting. Using advanced manufacturing, it is also possible to produce more complex porous structures with improved mechanical performance, potentially matching the modulus of elasticity of local bone"[346] (Sidambe, 2014).

3D bioprinting

Just as three dimensional metal printing, also "3D bioprinting technology has attracted enormous attention as it enabled 3D printing of a multitude of biocompatible materials, different types of cells and other supporting growth factors into complex functional living tissues in a 3D format"[347] (Zhang and Zhang, 2015). Additive manufacturing of biomaterials provides many opportunities for fabrication of complex tissue structures, which are difficult to fabricate by traditional manufacturing methods (Ren et al, 2014). "An integrated approach with a combination of technologies from the fields of engineering, biomaterials science, cell biology, physics, and medicine is required to address these complexities. Meeting this challenge is being made possible by directing the 3D bioprinting to manufacture biomimetic-shaped 3D structures,

[345] Lin, D; Nian, Q; Deng, BW; Jin, SY; Hu, YW; Wang, WQ; Cheng, GJ. 2014. Three-Dimensional Printing of Complex Structures: Man Made or toward Nature? ACS Nano, vol. 8, OCT, page 9710 [89]

[346] Sidambe, AT. 2014. Biocompatibility of Advanced Manufactured Titanium Implants – A Review. Materials, vol. 7, DEC, page 8168 [131]

[347] Zhang, XY; Zhang, YD. 2015. Tissue Engineering Applications of Three-Dimensional Bi-oprinting. Cell Biochem. Biophys., vol. 72, JUL, page 777 [158]

using organ/tissue images, obtained from magnetic resonance imaging and computerized tomography, and employing computer-aided design and manufacturing technologies"[348] (Zhang and Zhang, 2015).

"A major advantage of this technology is its ability for simultaneously 3D printing various cell types in defined spatial locations, which makes this technology applicable to regenerative medicine to meet the need for suitable for transplantation suitable organs and tissues. 3D bioprinting is yet to successfully overcome the many challenges related to building 3D structures that closely resemble native organs and tissues, which are complex structures with defined microarchitecture and a variety of cell types in a confined area"[349] (Zhang and Zhang, 2015).

However, "additive manufacturing is facing technical problems in printing user-prepared biomaterials. New biomaterials have uncertainty in physical properties, such as viscosity and surface tension coefficient. Therefore, the 3D printing process requires many trials to achieve proper printing parameters, such as printing layer thickness, maximum printing line distance and printing nozzle's feeding speed; otherwise, the desired computer-aided design (CAD) file will not be printed successfully in 3D printing"[350] (Ren et al, 2014). "The current 3D bioprinting technologies need to be improved with respect to the mechanical strength and integrity in the manufactured constructs as the presently used biomaterials are not of optimal viscosity. A better understanding of the tissue/organ microenvironment, which consists of multiple types of cells, is imperative for successful 3D bioprinting"[351] (Zhang and Zhang, 2015). Yoo (2014) points out that there is a lack of effective design software for printing and prototyping of tissues and scaffolds.

3.4 Summary: Barriers and drivers in sustainable manufacturing technologies

3.4.1 Sustainability in manufacturing

A general barrier to the adoption of sustainable manufacturing technologies is the fact that management needs to balance business profit with environmental impacts and benefits and is

[348] Zhang, XY; Zhang, YD. 2015. Tissue Engineering Applications of Three-Dimensional Bi-oprinting. Cell Biochem. Biophys., vol. 72, JUL, page 777 [158]
[349] Zhang, XY; Zhang, YD. 2015. Tissue Engineering Applications of Three-Dimensional Bi-oprinting. Cell Biochem. Biophys., vol. 72, JUL, page 777 [158]
[350] Ren, X; Zhang, QW; Liu, KW; Li, HL; Zhou, JG. 2014. Modeling of pneumatic valve dis-penser for printing viscous biomaterials in additive manufacturing. Rapid Prototyping J., vol. 20, 6, page 434 [118]
[351] Zhang, XY; Zhang, YD. 2015. Tissue Engineering Applications of Three-Dimensional Bi-oprinting. Cell Biochem. Biophys., vol. 72, JUL, page 777 [158]

challenged by a low realisation of market benefits (Granly and Webo, 2014). For example, enterprises have difficulties in allocating resources to initiatives that are not viewed as being directly related to their core function of manufacturing the product or providing the service (Cote et al, 2008).

In a similar vein, one barrier to the adoption of sustainable manufacturing technologies is the challenges in cost-benefit analysis. Firms' metrics typically fall into product-level metrics across the life cycle and facility-level metrics. Neither is sufficient for firm-wide cost-benefit analyses of modifications that affect multiple products and value-chain stages. Moreover, modifications to products' design, material procurement, manufacturing, energy/water use, distribution, use, and disposal often create trade-offs, improving some aspects while worsening others (Meinrenken et al, 2014). Hence, managerial decision making with respect to improving sustainability can be quite tricky.

Indeed, it has been shown that a firm's proficiency in leveraging IT technical infrastructure flexibility, IT personnel skills and IT-business alignment enables the integration of IT in the environmental management processes to improve environmental performance (Wang et al, 2015). Moreover, current IT systems can support the collection of all the information needed using computer-aided design (CAD), enterprise resource planning (ERP), and product life-cycle management (PLM) systems. For example, suppliers can provide component information to enable the manufacturer's design for disassembly and recycling analysis (Kuo, 2010). Similarly, current IT systems make it possible to establish system of key performance indicators (KPIs) that evaluate sustainability of the company's products across its brands and operating countries, and can be determined at any level (single product, brands, or regions) (Meinrenken et al, 2014).

If general standards and communication aspects are in, customer's awareness is much more likely to follow than in cases where information about technologies is hidden (Ruhnau and Bunzel, 2014). Local authorities can also play an important role in driving sustainable manufacturing technologies. For example, local authorities can develop Sustainable Product Service Systems enabling policies as well as supporting novel networks of stakeholders (Vezzoli et al, 2015).

Table 11. Barriers and drivers in sustainable manufacturing technologies, sustainability in manufacturing

	Barriers	Drivers
Environmental Context	• Management needs to balance business profit with environmental impacts and benefits, and is challenged by a low realisation of market benefits • Life cycle assessment methodologies not mature enough to be applied at the scale	• If general standards and communication aspects are in place (e.g. CO_2 emissions and fuel consumption) customer's awareness, and hence, companies' interest to operate accordingly is much more likely to follow than in cases where in-

	of entire product portfolios: neither product-level metrics nor facility-level metrics are sufficient for firm-wide cost-benefit analyses that affect multiple products and value-chain stages	formation about technologies is hidden • Local authorities can play an important role in developing sustainability-enhancing policies as well as supporting novel networks of stakeholders
Organizational Context	• General challenges with respect to employing sustainable manufacturing technologies relate to employee buy-in, competence and time, e.g. enterprises have difficulties in allocating resources to initiatives that are not viewed as directly related to their core function • Difficulty in combining multiple expertise the sustainable manufacturing technologies typically require • Challenging to manage variety throughout the entire product life cycle; firms have to balance dual goals of reducing variation and promoting variation in their product configuration activities	• Firm's proficiency in leveraging IT technical infrastructure flexibility, IT personnel skills and IT-business alignment enables the integration of IT in the environmental management processes to improve environmental performance
Technological Context	• Difficulty in gaining all the information necessary to plan for the recycling evaluation • Difficult to manage variety throughout the entire products life cycle; firms have to balance the dual goals of reducing variation and promoting variation in their product configuration activities • Modifications to products' design, material procurement, manufacturing, energy/water use, distribution, use, and disposal often create trade-offs, improving some aspects while worsening others • Life cycle assessment methodologies are currently not mature enough to be applied at the scale of entire product portfolios, e.g. integrated methods for part design and product development and integrated product-service lifecycle are needed	• Current IT systems can support the collection of all the necessary information using computer-aided design (CAD), enterprise resource planning (ERP), and product life-cycle management (PLM) systems so that suppliers can provide component information to enable the manufacturer's design for disassembly and recycling analysis • Current IT systems make it possible to establish system of key performance indicators (KPIs) that evaluate company's products across its brands and operating countries including annual figures (environmental, operational, and financial) across the value chain and can be determined at any level (single product, brands, or regions)

3.4.2 Energy efficiency

One driver for the formulation of new, more sustainable managerial practices combining energy efficiency and product innovation are efficiency considerations, market attention, and greening of innovation. They make company management consider more carefully the specificities and interactions of different types of products and process innovations and their environmental implications (Gerstlberger et al, 2014). Scale and supply-chain development do affect the adoption of sustainable technologies. For example, "the role of innovation, importance of manufacturing scale and opportunity for global collaboration leads to an increase in the installed photovoltaics capacity”[352] (Goodrich et al, 2013). Moreover, “the Internet of Things paradigm promises to increase the visibility and awareness of energy consumption, thanks to smart sensors and smart meters at the machine and production line level”[353] (Shrouf and Miragliotta, 2015).

Within the Technological Context, advantages of advanced manufacturing techniques include design flexibility, reduced processing costs, reduced waste, and the opportunity to more easily manufacture complex or custom-shaped structures (Sidambe, 2014). For example, the adoption of additive manufacturing technology can be used to reach transparency in terms of energy and financial inputs to manufacturing operations (Baumers et al, 2013). Similarly, an improved power monitoring is necessary for the quantification of energy efficiency. It helps to limit the expensive peak power use and control the process stability (Humphrey et al, 2014).

On the other hand, “ad hoc power measurement in industrial settings, and hence minimization of energy consumption, is often complicated. For example, wiring plans for machines sometimes do not reflect changes applied after installation or might be missing altogether, commercially available power measurement devices are often expensive”[354] (Humphrey et al, 2014).

Table 12. Barriers and drivers in sustainable manufacturing technologies, energy efficiency

	Barriers	Drivers
Environmental Context		• Scale and supply-chain development do affect the adoption of sustainable technologies, e.g. the role of innovation, importance of manufacturing scale and opportunity for global collaboration led to increase the installed photovoltaics capacity • The Internet of Things paradigm promises to increase the visibility and awareness of energy consumption, thanks to smart sensors and smart meters at the machine and production line level
Organizational Context		• Efficiency considerations, market attention, and greening of innovation make company management to consider more carefully the specificities and interactions of different types of products and process innovations and their environmental implications
Technological	• Ad hoc power measurement in indus-	• Improved power monitoring allows for the

352 Goodrich, AC; Powell, DM; James, TL; Woodhouse, M; Buonassisi, T. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci., vol. 6, OCT, page 2811 [59]

353 Shrouf, F; Miragliotta, G. 2015. Energy management based on Internet of Things: prac-tices and framework for adoption in production management. J. Clean Prod., vol. 100, AUG 1, page 235 [129]

354 Shrouf, F; Miragliotta, G. 2015. Energy management based on Internet of Things: prac-tices and framework for adoption in production management. J. Clean Prod., vol. 100, AUG 1, page 469 [70]

Context	trial settings, and hence minimization of energy consumption, is often complicated, e.g. wiring plans for machines sometimes do not reflect changes applied after installation or might be missing altogether, commercially available power measurement devices are often expensive	quantification of energy efficiency, the curbing of expensive peak power use and the control of the process stability • A better knowledge of the quantity and variety of parts demanded and the resulting ability to fully utilize the available machine capacity have an impact on process efficiency, e.g. cost minimization in additive manufacturing may lead to the minimization of process energy consumption

3.4.3 Biomanufacturing & sustainable nanotechnology

When considering new customer offerings, the unique advantage of nanotechnology is due to nanoscale physical and chemical properties that are quite different from those encountered in microscopic or macroscopic materials and devices. For example, integrating advanced nanotechnology with biotechnology helps to improve enzyme activity, stability, capability and engineering performances in bioprocessing applications (Misson et al, 2015). Fibres and fibre reinforced polymer composite products offer many significant benefits such as light-weight, superior mechanical properties, extended service life, low maintenance and resistance to corrosion (Kalla et al, 2012). They also provide positive environmental benefits with respect to ultimate disposability and raw material use (Postek et al, 2008). Fibres such as ones made from seed (coir) and animals (chicken feather) improve sustainability as they are secondary or made from waste products (Ramamoorthy et al, 2015).

However, scaling of operations can be a challenge. Biocomposites are explored at lab scales but they have not yet found large-scale commercial applications (Namvar et al, 2014). For example, in 3D bioprinting the mechanical strength of the printed materials and integrity of the manufactured constructs needs further improvement (Zhang and Zhang, 2015). New biomaterials have uncertainty in physical properties, such as viscosity and surface tension coefficient. Therefore, the 3D printing process requires a large number of trials in order to achieve proper printing parameters (Ren et al, 2014). There is a lack of an effective design software for 3D printing and prototyping also (Yoo, 2014). The application of state-of-the-art process systems engineering technologies is limited for small scale processes. The limitation due to the cost-benefit ratio is particularly high when attempting to optimise process operation, in comparison to process design topics (Dunnebier, 2008).

Similarly to other advanced manufacturing technologies, technical opportunities of biomanufacturing and sustainable nanotechnology need to be converted into concrete benefits with quantifiable impact. For example, nanomaterials can provide tailorablity beyond a traditional materials assuming that tailorability is integrated into manufacturing and design methods to further optimize the performance, cost and durability (Vaia, 2012).

Another barrier, in nano scale manufacturing, is a need to define nano-protective environmental health and safety practices (Engeman et al, 2013). Indeed, ethical and social implications of nanotechnology encompass many key areas associated with development, such as privacy, security, the environment, and food and agriculture (Khan, 2014). The potential adverse human health effects of manufactured nanomaterial exposure are not yet fully understood, and exposures in humans are mostly uncharted (Engeman et al, 2013). The basic processes common to manufacturing are not generally in place for nanotechnology-based products: qualification of raw materials, continuous synthesis methods, process monitoring and control, in-line and off-line characterization of product for quality control purposes and validation by standard reference materials (Postek et al, 2008). For example, nanoparticle's manufacturing technology challenges include operations ranging from particle formation, coating, dispersion, to characterization, modelling and simulation (Zhao et al, 2003).

Finally, biomanufacturing and sustainable nanotechnology require a combination of multiple expertises. For example, manufacturing of biocomposites from renewable sources is a challenging task involving metals, polymers and ceramics (Namvar et al, 2014). Engineering nanotechnology reliably into useful applications and products requires knowledge of manufacturing at the nanoscale, integration of nanoscale materials and devices with more conventional technology and predictive modelling (Romig, 2004).

Table 13. Barriers and drivers in sustainable manufacturing technologies, biomanufacturing & sustainable nanotechnology

	Barriers	Drivers
Environmental Context	• Need to convert technical opportunities into concrete benefits with quantifiable impact • Ethical and social implications of nanotechnology encompass many key areas associated with development, such as privacy, security, the environment and food and agriculture • Need to identify the needs of manufactured nanomaterial companies in developing nano-protective environmental health and safety practices	• New materials are emerging from secondary sources or from waste products; provide positive environmental benefits with respect to ultimate disposability and raw material use • The intersection of nano-based metamaterials and nanostructured devices with biotechnology epitomizes the technological promise of autonomous systems and enhanced human-machine interfaces
Organizational Context	• Must be able to combine multiple expertise, e.g. manufacturing of biocomposites from renewable sources is a challenging task, involving metals, polymers and ceramics • Engineering nanotechnology reliably into useful applications and products requires a knowledge of manufacturing at the nanoscale, integration of nanoscale materials and devices with more conventional technology and predictive modelling	

Technological Context	• The application of state-of-the-art process systems engineering technologies is limited for small scale processes; the limitation due to the cost-benefit ratio is particularly high when attempting to optimise process operation, in comparison to process design topics • Scaling of operations can be a challenge, e.g. biocomposites are explored at lab scales but they have not yet found large-scale commercial applications • Lack of an effective design software for 3D printing and prototyping • The current 3D bioprinting technologies need to be improved with respect to the mechanical strength and integrity in the manufactured constructs, e.g. new biomaterials have uncertainty in physical properties, such as viscosity and surface tension coefficient • Continuous, process-like manufacturing places special requirements to the Six Sigma toolbox e.g. with respect to advanced control, dynamic simulation and dynamic optimisation	• Continuous manufacturing promises sustained operation with consistent product quality, reduced equipment size, high-volumetric productivity, streamlined process flow, low-process cycle times and reduced capital and operating cost • The unique advantage of nanotechnology is due to nanoscale physical and chemical properties that are quite different from those encountered in microscopic or macroscopic materials and devices • Integrating advanced nanotechnology with biotechnology helps to improve enzyme activity, stability, capability and engineering performances in bioprocessing applications • Advanced manufacturing techniques could replace the machining or casting of metal alloys in the manufacture of devices because of associated advantages that include design flexibility, reduced processing costs, reduced waste and the opportunity to more easily manufacture complex or custom-shaped structures

4 References

1. Ahuja, B; Karg, M; Schmidt, M. 2015. Additive Manufacturing in Production – Challenges and Opportunities. LASER 3D MANUFACTURING II, FEB 10–12, 2015
2. Angrish, A. 2014. A Critical Analysis of Additive Manufacturing Technologies for Aerospace Applications. 2014 IEEE AEROSPACE CONFERENCE, MAR 01–08, 2014
3. Baumers, M; Tuck, C; Wildman, R; Ashcroft, I; Rosamond, E; Hague, R. 2013. Transparency Built-in Energy Consumption and Cost Estimation for Additive Manufacturing. J. Ind. Ecol., vol. 17, JUN, pp. 418–431
4. Bechtold, F. 2009. A Comprehensive Overview on Today's Ceramic Substrate Technologies. 2009 EUROPEAN MICROELECTRONICS AND PACKAGING CONFERENCE (EMPC 2009), VOLS 1 AND 2, JUN 16–18, 2009, pp. 798–809
5. Bi, ZM; Liu, YF; Baumgartner, B; Culver, E; Sorokin, JN; Peters, A; Cox, B; Hunnicutt, J; Yurek, J; O'Shaughnessey, S. 2015. Reusing industrial robots to achieve sustainability in small and medium-sized enterprises (SMEs). Ind. Robot, vol. 42, 3, pp. 264–273
6. Blackman, ID; Holland, CP; Westcott, T. 2013. Motorola's global financial supply chain strategy. Supply Chain Manag., vol. 18, 2, pp. 132–147
7. Bond, LJ. 2014. Through the Looking Glass: The Future for NDE?. 40TH ANNUAL REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE EVALUATION: INCORPORATING THE 10TH INTERNATIONAL CONFERENCE ON BARKHAUSEN NOISE AND MICROMAGNETIC TESTING, VOLS 33A & 33B, JUL 21–26, 2013, pp. 21–35
8. Bond, LJ. 2015. Needs and opportunities: nondestructive evaluation for energy systems. SMART MATERIALS AND NONDESTRUCTIVE EVALUATION FOR ENERGY SYSTEMS 2015, MAR 09–10, 2015
9. Braun, T; Bauer, J; Georgi, L; Becker, KF; Koch, M; Aschenbrenner, R; Lang, KD. 2012. Enhancement of Barrier Properties of Encapsulants for Harsh Environment Applications. 2012 IEEE 62ND ELECTRONIC COMPONENTS AND TECHNOLOGY CONFERENCE (ECTC), MAY 29–JUN 01, 2012, pp. 1418–1425
10. Braun, T; Hausel, F; Bauer, J; Wittler, O; Mrossko, R; Bouazza, M; Becker, KF; Oestermann, U; Koch, M; Bader, V; Minge, C; Aschenbrenner, R; Reichl, H. 2008. Nanoparticle enhanced encapsulants for improved humidity resistance. 58TH ELECTRONIC COMPONENTS & TECHNOLOGY CONFERENCE, PROCEEDINGS, 2008, pp. 198–206
11. Brice, CA. 2011. UNINTENDED CONSEQUENCES: HOW QUALIFICATION CONSTRAINS INNOVATION. PROCEEDINGS OF THE 1ST WORLD CONGRESS ON INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING (ICME), JUL 10–14, 2011, pp. 241–246
12. Brogardh, T. 2007. Present and future robot control development – An industrial perspective. Annu. Rev. Control, vol. 31, 1, pp. 69–79
13. Camoin Associates. 2011. Research by Camoin Associates, Presentation by Robert M. Ady to the International Economic Development Council, September 18, 2011

14. Caro, S; Garnier, S; Furet, B; Klimchik, A; Pashkevich, A. 2014. Workpiece Placement Optimization for Machining Operations with Industrial Robots. 2014 IEEE/ASME INTERNATIONAL CONFERENCE ON ADVANCED INTELLIGENT MECHATRONICS (AIM), JUL 08–11, 2014, pp. 1716–1721
15. Cavada, J; Fadon, F. 2013. ROBOTIC SOLUTIONS APPLIED TO PRODUCTION AND MEASUREMENT OF MARINE PROPELLERS. PROCEEDINGS OF THE ASME 11TH BIENNIAL CONFERENCE ON ENGINEERING SYSTEMS DESIGN AND ANALYSIS, 2012, VOL 3, JUL 02–04, 2012, pp. 275–281
16. Chand, D., Hachey, G., Hunton, J., Owhoso, V. & Vasudevan, S. 2005. A balanced score-card based framework for assessing the strategic impacts of ERP systems, Computers in Industry, 56, pp.558-572.
17. Chang, DN; Lee, CKM; Chen, CH. 2014. Review of life cycle assessment towards sustainable product development. J. Clean Prod., vol. 83, NOV 15, pp. 48–60
18. Chatterjee, P; Athawale, VM; Chakraborty, S. 2010. Selection of industrial robots using compromise ranking and outranking methods. Robot. Comput.-Integr. Manuf., vol. 26, OCT, pp. 483–489
19. Chen, HP; Xi, N. 2012. Automated Robot Tool Trajectory Connection for Spray Forming Process. J. Manuf. Sci. Eng.-Trans. ASME, vol. 134, APR
20. Chen, LX; Chen, YH; Pang, Z. 2011. Dynamic Pricing and Inventory Control in a Make-to-Stock Queue With Information on the Production Status. IEEE Trans. Autom. Sci. Eng., vol. 8, APR, pp. 361–373
21. Chhabra, M; Singh, R. 2011. Rapid casting solutions: a review. Rapid Prototyping J., vol. 17, 5, pp. 328–350
22. Chioreanu, A; Brad, S; Brad, E. 2013. Knowledge Modelling of E-maintenance in Industrial Robotics. INTERDISCIPLINARY RESEARCH IN ENGINEERING: STEPS TOWARDS BREAKTHROUGH INNOVATION FOR SUSTAINABLE DEVELOPMENT, FEB 25–MAR 01, 2013, pp. 603–610
23. Chou, JS; Hong, JH. 2013. Assessing the impact of quality determinants and user characteristics on successful enterprise resource planning project implementation. J. Manuf. Syst., vol. 32, OCT, pp. 792–800
24. Cipollone, R. 2013. Sliding vane rotary compressor technology and energy saving. 8TH INTERNATIONAL CONFERENCE ON COMPRESSORS AND THEIR SYSTEMS, SEP 09–10, 2013, pp. 27–54
25. Colledani, M; Tolio, T; Fischer, A; Iung, B; Lanza, G; Schmitt, R; Vancza, J. 2014. Design and management of manufacturing systems for production quality. CIRP Annals – Manufacturing Technology. CIRP Ann-Manuf. Technol., vol. 63, 2, pp. 773–796
26. Cooper, KP. 2014. Laser-based additive manufacturing: Where it has been, where it needs to go. LASER 3D MANUFACTURING, FEB 05–06, 2014

27. Cooper, KP; Wachter, RF. 2014. Cyber-enabled manufacturing systems for additive manufacturing. Rapid Prototyping J., vol. 20, 5, pp. 355–359
28. Cormia, RD; Oye, MM; Nguyen, A; Skiver, D; Shi, M; Torres, Y. 2014. Integrating Electron Microscopy into Nanoscience and Materials Engineering Programs. SCANNING MICROSCOPIES 2014, SEP 16–18, 2014
29. Cote, RP; Lopez, J; Marche, S; Perron, GM; Wright, R. 2008. Influences, practices and opportunities for environmental supply chain management in Nova Scotia SMEs. J. Clean Prod., vol. 16, 15, pp. 1561–1570
30. Cunico, MWM; de Carvalho, J. 2013. Design of an FDM positioning system and application of an error-cost multiobjective optimization approach. Rapid Prototyping J., vol. 19, 5, pp. 344–352
31. Das, B. 2001. Ergonomics considerations and management action in the implementation of industrial robots. Hum. Factors Ergon. Manuf., vol. 11, SUM, pp. 269–285
32. Dawes, J; Bowerman, R; Trepleton, R. 2015. Introduction to the Additive Manufacturing Powder Metallurgy Supply Chain Exploring the production and supply of metal powders for AM processes. Johns. Matthey Technol. Rev., vol. 59, JUL, pp. 243–256
33. Dias, JCQ; Calado, JMF; Osorio, AL; Morgado, LF. 2009. RFID together with multi-agent systems to control global value chains. Annu. Rev. Control, vol. 33, DEC, pp. 185–195
34. Ding, H; Wijaya, K; Reissig, G; Stursberg, O. 2011. Optimizing Motion of Robotic Manipulators in Interaction with Human Operators. INTELLIGENT ROBOTICS AND APPLICATIONS, PT I: ICIRA 2011, DEC 06–08, 2011, pp. 520–531
35. Dunnebier, G. 2008. Troubleshooting and process optimisation by integrating CAPE tools and Six Sigma methodology. 18TH EUROPEAN SYMPOSIUM ON COMPUTER AIDED PROCESS ENGINEERING, JUN 01–04, 2008, pp. 943–948
36. Dutta, D; Bose, I. 2015. Managing a Big Data project: The case of Ramco Cements Limited. Int. J. Prod. Econ., vol. 165, JUL, pp. 293–306
37. ElMaraghy, H; Schuh, G; ElMaraghy, W; Piller, F; Schonsleben, P; Tseng, M; Bernard, A. 2013. Product variety management. CIRP Ann-Manuf. Technol., vol. 62, 2, pp. 629–652
38. Emmanouilidis, C; Riziotis, C. 2015. Wireless Condition Monitoring Integrating Smart Computing and Optical Sensor Technologies. ENGINEERING ASSET MANAGEMENT – SYSTEMS, PROFESSIONAL PRACTICES AND CERTIFICATION, OCT 30–NOV 01, 2013, pp. 1389–1400
39. Engeman, CD; Baumgartner, L; Carr, BM; Fish, AM; Meyerhofer, JD; Satterfield, TA; Holden, PA; Harthorn, BH. 2013. The Hierarchy of Environmental Health and Safety Practices in the US Nanotechnology Workplace. J. Occup. Environ. Hyg., vol. 10, SEP 1, pp. 487–495

40. Espig, M; Siegel, F; Hammerschmidt, J; Willert, A; Baumann, RR. 2012. Central Challenges When up Scaling the Manufacturing of Thin-Film Battery Applications. NIP28: 28TH INTERNATIONAL CONFERENCE ON DIGITAL PRINTING TECHNOLOGIES / DIGITAL FABRICATION 2012, SEP 09–13, 2012, pp. 168–170
41. Espig, M; Siegel, F; Hammerschmidt, J; Willert, A; Baumann, RR. 2012. Central Challenges When up Scaling the Manufacturing of Thin-Film Battery Applications. NIP28: 28TH INTERNATIONAL CONFERENCE ON DIGITAL PRINTING TECHNOLOGIES / DIGITAL FABRICATION 2012, 0, pp. 168–170
42. European Commission. 2005. Synthesis report of the key technologies expert group (2005); Creative system disruption: towards a research strategy beyond Lisbon. ftp://ftp.cordis.europa.eu/pub/foresight/docs/key-technologies-report.pdf ref 26.4.2016
43. European Commission. 2009a. A Strategy for ICT R&D and Innovation in Europe: Raising the Game COM (2009) 116. http://eur-lex.europa.eu/legal-content/EN/ TXT/ PDF/?uri=CELEX:52009DC0116&from=EN
44. European Commission. 2009b. Preparing for our future: Developing a common strategy for key enabling technologies in the EU COM (2009) 1257. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN
45. European Commission. 2009c. Preparing for our future: Developing a common strategy for key enabling technologies in the EU. Staff Working Paper (SEC (2009) 1257). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009DC0512&from=EN ref 26.4.2016
46. European Commission. 2009d. Science, Technology and Competitiveness key figures report 2008/2009. https://ec.europa.eu/research/era/pdf/key-figures-report2008-2009_en.pdf ref 26.4.2016
47. European Commission. 2016a. EU Task Force for Advanced Manufacturing Technologies for Clean Production http://ec.europa.eu/growth/industry/innovation/advanced-manufacturing/index_en.htm ref 26.4.2016
48. European Commission. 2016b. What are KETs and why are they important? http://ec.europa.eu/growth/industry/key-enabling-technologies/description/index_en.htm ref 26.4.2016
49. European Commission. 2016c. Regional Good Practices and Pilot / Demonstrator Projects for Advanced Manufacturing https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/advanced_manufacturing/instructions ref 26.4.2016
50. Everton, S; Dickens, P; Tuck, C; Dutton, B. 2015. Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing. LASER 3D MANUFACTURING II, FEB 10–12, 2015

51. Executive Office of the President. 2011. Report to the President on Ensuring American Leadership in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2011, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf ref 26.4.2016
52. Executive Office of the President. 2012. Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing, President's Council of Advisors on Science and Technology, 2012, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf ref 26.4.2016
53. Fasano, M; Bigdeli, MB; Sereshk, MRV; Chiavazzo, E; Asinari, P. 2015. Thermal transmittance of carbon nanotube networks: Guidelines for novel thermal storage systems and polymeric material of thermal interest. Renew. Sust. Energ. Rev., vol. 41, JAN, pp. 1028–1036
54. Fawcett, SE; Magnan, GM; McCarter, MW. 2008. Benefits, barriers, and bridges to effective supply chain management. Supply Chain Manag., vol. 13, 1, pp. 35–48
55. Fischer, A; Rommel, S; Bauernhansl, T. 2013. New Fiber Matrix Process with 3D Fiber Printer A Strategic In-process Integration of Endless Fibers Using Fused Deposition Modeling (FDM). DIGITAL PRODUCT AND PROCESS DEVELOPMENT SYSTEMS, OCT 10–11, 2013, pp. 167–175
56. Gerstlberger, W; Knudsen, MP; Stampe, I. 2014. Sustainable Development Strategies for Product Innovation and Energy Efficiency. Bus. Strateg. Environ., vol. 23, FEB, pp. 131–144
57. Ghelichi, A; Abdelgawad, A. 2014. RFID Applications in Inventory Management Based on Kanban System. INTERNATIONAL CONFERENCE ON ELECTRICAL AND ELECTRONIC ENGINEERING (EEE 2014), APR 26–27, 2014, pp. 132–135
58. Gmeiner, R; Deisinger, U; Schonherr, J; Lechner, B; Detsch, R; Boccaccini, AR; Stampfl, J. 2015. Additive Manufacturing of Bioactive Glasses and Silicate Bioceramics. J. Ceram. Sci. Technol., vol. 6, JUN, pp. 75–86
59. Goodrich, AC; Powell, DM; James, TL; Woodhouse, M; Buonassisi, T. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci., vol. 6, OCT, pp. 2811–2821
60. Gould, BD; Rodgers, JA; Schuette, M; Bethune, K; Louis, S; Rocheleau, R; Swider-Lyons, K. 2014. Performance of 3D-printed fuel cells and stacks. POLYMER ELECTROLYTE FUEL CELLS 14, OCT 05–09, 2014, pp. 935–944
61. Graetz, MJ; Doud, R. 2013. TECHNOLOGICAL INNOVATION, INTERNATIONAL COMPETITION, AND THE CHALLENGES OF INTERNATIONAL INCOME TAXATION. Columbia Law Rev., vol. 113, MAR, pp. 347–445

62. Granly, BM; Webo, T. 2014. EMS and sustainability: experiences with ISO 14001 and Eco-Lighthouse in Norwegian metal processing SMEs. J. Clean Prod., vol. 64, FEB 1, pp. 194–204
63. Handwerker, CA; Pollock, TM. 2014. Emerging Science and Research Opportunities for Metals and Metallic Nanostructures. JOM, vol. 66, JUL, pp. 1321–1341
64. Hart, CA; Snaddon, DR. 2014. THE ORGANISATIONAL PERFORMANCE IMPACT OF ERP SYSTEMS ON SELECTED COMPANIES. S. Afr. J. Ind. Eng., vol. 25, MAY, pp. 14–28
65. Hergel, J; Lefebvre, S. 2014. Clean color: Improving multi-filament 3D prints. Comput. Graph. Forum, vol. 33, MAY, pp. 469–478
66. Heyer, C. 2010. Human-Robot Interaction and Future Industrial Robotics Applications. IEEE/RSJ 2010 INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2010), OCT 18–22, 2010, pp. 4749–4754
67. Hilletofth, P; Lattila, L. 2012. Agent based decision support in the supply chain context. Ind. Manage. Data Syst., vol. 112, Sep 8, pp. 1217–1235
68. Hoshino, S; Seki, H; Naka, Y; Ota, J. 2010. Multirobot Coordination for Flexible Batch Manufacturing Systems Experiencing Bottlenecks. IEEE Trans. Autom. Sci. Eng., vol. 7, OCT, pp. 887–901
69. Hsieh, FS; Lin, JB. 2014. A Multiagent Approach for Managing Collaborative Workflows in Supply Chains. PROCEEDINGS OF THE 2014 IEEE 18TH INTERNATIONAL CONFERENCE ON COMPUTER SUPPORTED COOPERATIVE WORK IN DESIGN (CSCWD), MAY 21–23, 2014, pp. 71–76
70. Humphrey, S; Papadopoulos, H; Linke, B; Maiyya, S; Vijayaraghavan, A; Schmitt, R. 2014. Power measurement for sustainable high-performance manufacturing processes. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, pp. 466–471
71. Irani, Z. 2002. Information systems evaluation: navigating through the problem domain. Inf. Manage., vol. 40, OCT, pp. 11–24
72. Isenberg, DJ. 2008. The Global Entrepreneur. Harv. Bus. Rev., vol. 86, DEC, pp. 107–114
73. Jansen, B; Doubrovski, EL; Verlinden, JC. 2014. Animaris Geneticus Parvus Design of a complex multi-body walking mechanism. Rapid Prototyping J., vol. 20, 4, pp. 311–319
74. Kale, S; Dancholvichit, N; Okwudire, C. 2014. Comparative LCA of a linear motor and hybrid feed drive under high cutting loads. 6TH CIRP INTERNATIONAL CONFERENCE ON HIGH PERFORMANCE CUTTING (HPC2014), JUN 23–25, 2014, pp. 552–557
75. Kalla, DK; Dhanasekaran, PS; Zhang, BW; Asmatulu, R. 2012. SUSTAINABILITY OF FIBER REINFORCED COMPOSITES: STATUS AND VISION FOR FUTURE. PROCEEDINGS OF THE ASME INTERNATIONAL MECHANICAL ENGINEERING CONGRESS AND EXPOSITION 2011, VOL 3, NOV 11–17, 2011, pp. 167–173
76. Khan, AS. 2014. Ethics and Nanotechnology. 2014 IEEE INTERNATIONAL SYMPOSIUM ON ETHICS IN SCIENCE, TECHNOLOGY AND ENGINEERING, MAY 23–24, 2014

77. Kim, K; Kim, J; Kang, S; Kim, J; Lee, J. 2012. Vision-Based Bin Picking System for Industrial Robotics Applications. 2012 9TH INTERNATIONAL CONFERENCE ON UBIQUITOUS ROBOTS AND AMBIENT INTELLIGENCE (URAL), NOV 26–29, 2012, pp. 515–516

78. Kluz, R; Trzepiecinski, T. 2014. The repeatability positioning analysis of the industrial robot arm. Assem. Autom., vol. 34, 3, pp. 285–295

79. Kohl, H; Galeitzke, M; Steinhofel, E; Orth, R. 2014. Strategic Intellectual Capital Management as a Driver of Organisational Innovation. IFKAD 2014: 9TH INTERNATIONAL FORUM ON KNOWLEDGE ASSET DYNAMICS: KNOWLEDGE AND MANAGEMENT MODELS FOR SUSTAINABLE GROWTH, JUN 11–13, 2014, pp. 1481–1495

80. Konstantinov, KB; Cooney, CL. 2015. White Paper on Continuous Bioprocessing May 20–21, 2014 Continuous Manufacturing Symposium. J. Pharm. Sci., vol. 104, MAR, pp. 813–820

81. Koulouriotis, DE; Ketipi, MK. 2014. Robot evaluation and selection Part A: an integrated review and annotated taxonomy. Int. J. Adv. Manuf. Technol., vol. 71, MAR, pp. 1371–1394

82. Kuo, TC. 2010. The construction of a collaborative-design platform to support waste electrical and electronic equipment recycling. Robot. Comput.-Integr. Manuf., vol. 26, FEB, pp. 100–108

83. Lee, CGN; Kanarik, KJ; Gottscho, RA. 2014. The grand challenges of plasma etching: a manufacturing perspective. J. Phys. D-Appl. Phys., vol. 47, JUL 9

84. Lee, JY; Kang, HS; Noh, SD. 2014. MAS(2): an integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing. J. Clean Prod., vol. 66, Nov 1, pp. 146–163

85. Li, BB; Chen, HP; Jin, TD. 2014. Industrial Robotic Assembly Process Modeling Using Support Vector Regression. 2014 IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2014), SEP 14–18, 2014, pp. 4334–4339

86. Li, JH; Zeng, XL; Stevels, A. 2015. Ecodesign in Consumer Electronics: Past, Present, and Future. Crit. Rev. Environ. Sci. Technol., vol. 45, APR 18, pp. 840–860

87. Liaw, HC; Shirinzadeh, B. 2010. Constrained Motion Tracking Control of Piezo-Actuated Flexure-Based Four-Bar Mechanisms for Micro/Nano Manipulation. IEEE Trans. Autom. Sci. Eng., vol. 7, JUL, pp. 699–705

88. Lifton, VA; Lifton, G; Simon, S. 2014. Options for additive rapid prototyping methods (3D printing) in MEMS technology. Rapid Prototyping J., vol. 20, 5, pp. 403–412

89. Lin, D; Nian, Q; Deng, BW; Jin, SY; Hu, YW; Wang, WQ; Cheng, GJ. 2014. Three-Dimensional Printing of Complex Structures: Man Made or toward Nature? ACS Nano, vol. 8, OCT, pp. 9710–9715

90. Lindemann, C; Reiher, T; Jahnke, U; Koch, R. 2015. Towards a sustainable and economic selection of part candidates for additive manufacturing. Rapid Prototyping J., vol. 21, 2, pp. 216–227

91. Liu, CS; Liu, CC; Tai, YH; Lin, GZ. 2012. Implementation and Control for a Track Motion Robotic Manipulator. 2012 PROCEEDINGS OF SICE ANNUAL CONFERENCE (SICE), AUG 20–23, 2012, pp. 552–557
92. Liu, CW; Ostling, M; Hannon, JB. 2014. New materials for post-Si computing. MRS Bull., vol. 39, AUG, pp. 658–662
93. Lopes, J; Wurst, KH; Verl, A. 2013. Industrial Powerline Communication for Machine Tools and Industrial Robots. 2013 17TH IEEE INTERNATIONAL SYMPOSIUM ON POWER LINE COMMUNICATIONS AND ITS APPLICATIONS (ISPLC), MAR 24–27, 2013, pp. 351–356
94. Mahamood, RM; Akinlabi, ET; Shukla, M; Pityana, S. 2014. Revolutionary Additive Manufacturing: An Overview. Laser Eng., vol. 27, Apr 3, pp. 161–178
95. Maher, M; Smith, A; Margiotta, J. 2014. A synopsis of the Defense Advanced Research Projects Agency (DARPA) investment in additive manufacture and what challenges remain. LASER 3D MANUFACTURING, FEB 05–06, 2014
96. Mani, M; Lyons, KW; Gupta, SK. 2014. Sustainability Characterization for Additive Manufacturing. J. Res. Natl. Inst. Stand. Technol., vol. 119, SEP 22, pp. 419–428
97. McEwan, W; Butterfield, J. 2011. A Digital Methodology for the Design Process of Aerospace Assemblies with Sustainable Composite Processes & Manufacture. 14TH INTERNATIONAL CONFERENCE ON MATERIAL FORMING ESAFORM, 2011 PROCEEDINGS, APR 27–29, 2011, pp. 1683–1688
98. McFarlane, D; Giannikas, V; Wong, ACY; Harrison, M. 2013. Product intelligence in industrial control: Theory and practice. Annu. Rev. Control, vol. 37, APR, pp. 69–88
99. Meinrenken, CJ; Sauerhaft, BC; Garvan, AN; Lackner, KS. 2014. Combining Life Cycle Assessment with Data Science to Inform Portfolio-Level Value-Chain Engineering A Case Study at PepsiCo Inc. J. Ind. Ecol., vol. 18, OCT, pp. 641–651
100. Mellor, S; Hao, L; Zhang, D. 2014. Additive manufacturing: A framework for implementation. International Journal of Production Economics, vol 149, March 2014, pp. 194–201
101. Misson, M; Zhang, H; Jin, B. 2015. Nanobiocatalyst advancements and bioprocessing applications. J. R. Soc. Interface, vol. 12, JAN 6
102. Namvar, F; Jawaid, M; Tahir, PM; Mohamad, R; Azizi, S; Khodavandi, A; Rahman, HS; Nayeri, MD. 2014. Potential Use of Plant Fibres and their Composites for Biomedical Applications. BioResources, vol. 9, 3, pp. 5688–5706
103. Narayan, J. 2012. Nanoscience to nanotechnology to manufacturing transition. Int. J. Nanotechnol., vol. 9, Dec 10, pp. 914–941
104. Nath, AK; Saha, P; Salehi-Sangari, E. 2008. Transforming supply chains in digital content delivery: A case study in apple. Research and Practical Issues of Enterprise Information Systems II, Vol 2, OCT 14–16, 2007, pp. 1079–1089

105. Neto, P. 2013. Off-line Programming and Simulation from CAD Drawings: Robot-Assisted Sheet Metal Bending. 39TH ANNUAL CONFERENCE OF THE IEEE INDUSTRIAL ELECTRONICS SOCIETY (IECON 2013), NOV 10–14, 2013, pp. 4235–4240
106. Ng, CH; Chua, CK; Leong, KF. 2014. Teaching of additive manufacturing technology – A case study in the use of multimedia learning aids. HIGH VALUE MANUFACTURING: ADVANCED RESEARCH IN VIRTUAL AND RAPID PROTOTYPING, OCT 01–05, 2013, pp. 565–569
107. Ngai, EWT; Chau, DCK; Poon, JKL; Chan, AYM; Chan, BCM; Wu, WWS. 2012. Implementing an RFID-based manufacturing process management system: Lessons learned and success factors. J. Eng. Technol. Manage., vol. 29, JAN–MAR, pp. 112–130
108. Noel, M; Sodhi, MS; Lamond, BF. 2007. Tool planning for a lights-out machining system. J. Manuf. Syst., vol. 26, Apr 3, pp. 161–166
109. Palanivel, S; Sidhar, H; Mishra, RS. 2015. Friction Stir Additive Manufacturing: Route to High Structural Performance. JOM, vol. 67, MAR, pp. 616–621
110. Peruzzini, M; Germani, M; Marilungo, E. 2013. Design for sustainability of product-service systems in the extended enterprise. 20TH ISPE INTERNATIONAL CONFERENCE ON CONCURRENT ENGINEERING, SEP 02–06, 2013, pp. 314–323
111. Popovic, MA; Wade, MT; Oreutt, JS; Shainline, JM; Sun, C; Georgas, M; Moss, B; Kumar, E; Alloatti, L; Pavanello, F; Chen, YH; Nammari, K; Notaros, J; Atabaki, A; Leu, J; Stojanovic, V; Ram, RJ. 2015. Monolithic Silicon Photonics in a Sub-100nm SOI CMOS Microprocessor Foundry: Progress from Devices to Systems. SILICON PHOTONICS X, FEB 09–12, 2015
112. Postek, MT; Vladar, A; Dagata, J; Farkas, N; Ming, B; Sabo, R; Wegner, TH; Beecher, J. 2008. Cellulose Nanocrystals the Next Big Nano-thing? Instrumentation, Metrology, and Standards for Nanomanufacturing II, AUG 10, 2008
113. Poston, R.; Grabski, S. 2001. Financial impacts of enterprise resource planning implementations, International Journal of Accounting Information Systems, 2, pp.271-294.
114. Priarone, PC; Robiglio, M; Settineri, L; Tebaldo, V. 2015. Effectiveness of minimizing cutting fluid use when turning difficult-to-cut alloys. 22ND CIRP CONFERENCE ON LIFE CYCLE ENGINEERING, APR 07–09, 2015, pp. 341–346
115. Profijt, HB; Potts, SE; van de Sanden, MCM; Kessels, WMM. 2011. Plasma-Assisted Atomic Layer Deposition: Basics, Opportunities, and Challenges. J. Vac. Sci. Technol. A, vol. 29, SEP
116. Ramamoorthy, SK; Skrifvars, M; Persson, A. 2015. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. Polym. Rev., vol. 55, JAN 2, pp. 107–162
117. Rangan, RM; Rohde, SM; Peak, R; Chadha, B; Bliznakov, P. 2005. Streamlining product lifecycle processes: a survey of product lifecycle management implementations, directions, and challenges. J. Comput. Inf. Sci. Eng., vol. 5, SEP, pp. 227–237

118. Ren, X; Zhang, QW; Liu, KW; Li, HL; Zhou, JG. 2014. Modeling of pneumatic valve dispenser for printing viscous biomaterials in additive manufacturing. Rapid Prototyping J., vol. 20, 6, pp. 434–443

119. Romero-Garcia, S; Shen, B; Merget, F; Marzban, B; Witzens, J. 2015. Alignment Tolerant Couplers for Silicon Photonics. IEEE J. Sel. Top. Quantum Electron., vol. 21, NOV–DEC

120. Romig, AD. 2004. Nanotechnology: Scientific challenges and societal benefits and risks. Metall. Mater. Trans. A-Phys. Metall. Mater. Sci., vol. 35A, DEC, pp. 3641–3648

121. Ruhnau, T; Bunzel, WM. 2014. Sustainability in Automotive Pricing. SUSTAINABLE AUTOMOTIVE TECHNOLOGIES 2013, SEP 25–27, 2013, pp. 143–150

122. Salonitis, K; Ball, P. 2013. Energy efficient manufacturing from machine tools to manufacturing systems. FORTY SIXTH CIRP CONFERENCE ON MANUFACTURING SYSTEMS 2013, MAY 29–30, 2013, pp. 634–639

123. Salvador, F; Chandrasekaran, A; Sohail, T. 2014. Product configuration, ambidexterity and firm performance in the context of industrial equipment manufacturing. J. Oper. Manag., vol. 32, MAY, pp. 138–153

124. Science and Technology Policy Institute. 2010. White Papers on Advanced Manufacturing Questions. https://www.whitehouse.gov/sites/default/files/microsites/ostp/advanced-manuf-papers.pdf ref 26.4.2016

125. Secundo, G; Passiante, G; Romano, A; Moliterni, P. 2013. Developing the Next Generation of Engineers for Intelligent and Sustainable Manufacturing: A Case Study. Int. J. Eng. Educ, vol. 29, 1, pp. 248–262

126. Selvaraja, SK; Winroth, G; Locorotondo, S; Murdoch, G; Milenin, A; Delvaux, C; Ong, P; Pathak, S; Xie, WQ; Sterckx, G; Lepage, G; Van Thourhout, D; Bogaerts, W; Van Campenhout, J; Absil, P. 2014. 193nm immersion lithography for high performance silicon photonic circuits. OPTICAL MICROLITHOGRAPHY XXVII, FEB 25–27, 2014

127. Shi, L; Dames, C; Lukes, JR; Reddy, P; Duda, J; Cahill, DG; Lee, J; Marconnet, A; Goodson, KE; Bahk, JH; Shakouri, A; Prasher, RS; Felts, J; King, WP; Han, B; Bischof, JC. 2015. Evaluating Broader Impacts of Nanoscale Thermal Transport Research. Nanoscale Microscale Thermophys. Eng., vol. 19, APR 3, pp. 127–165

128. Shore, P; Morantz, P. 2012. Ultra-precision: enabling our future. Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci., vol. 370, AUG 28, pp. 3993–4014

129. Shrouf, F; Miragliotta, G. 2015. Energy management based on Internet of Things: practices and framework for adoption in production management. J. Clean Prod., vol. 100, AUG 1, pp. 235–246

130. Shukor, SA; Axinte, DA. 2009. Manufacturability analysis system: issues and future trends. Int. J. Prod. Res., vol. 47, 5, pp. 1369–1390

131. Sidambe, AT. 2014. Biocompatibility of Advanced Manufactured Titanium Implants – A Review. Materials, vol. 7, DEC, pp. 8168–8188

132. Silcher, S; Dinkelmann, M; Minguez, J; Mitschang, B. 2013. Advanced Product Lifecycle Management by Introducing Domain-Specific Service Buses. ENTERPRISE INFORMATION SYSTEMS, ICEIS 2012, JUN 28–JUL 01, 2012, pp. 92–107

133. Singh, B; Sewell, N. 2012. Knowledge based process planning and design for Additive Manufacturing (KARMA). INNOVATIVE DEVELOPMENTS ON VIRTUAL AND PHYSICAL PROTOTYPING, SEP 28–OCT 01, 2011, pp. 619–624

134. Slotwinski, JA. 2014. Additive Manufacturing: Overview and NDE Challenges. 40TH ANNUAL REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE EVALUATION: INCORPORATING THE 10TH INTERNATIONAL CONFERENCE ON BARKHAUSEN NOISE AND MICROMAGNETIC TESTING, VOLS 33A & 33B, JUL 21–26, 2013, pp. 1173–1177

135. Sorrell, S.; Schleich, J.; Scott, S.; O'Malley, E.; Trace, F.; Boede, U.; Ostertag, K. and Radgen, P. 2000. Reducing barriers to energy efficiency in public and private organizations, SPRU

136. Spathis, C; Constantinides, S. 2003. The usefulness of ERP systems for effective management, Industrial Management and Data Systems, 103(9), pp. 677-685.

137. Sztipanovits, J; Bapty, T; Neema, S; Howard, L; Jackson, E. 2014. OpenMETA: A Model- and Component-Based Design Tool Chain for Cyber-Physical Systems. FROM PROGRAMS TO SYSTEMS: THE SYSTEMS PERSPECTIVE IN COMPUTING, APR 06, 2014, pp. 235–248

138. Tabanli, RM; Ertay, T. 2013. Value stream mapping and benefit-cost analysis application for value visibility of a pilot project on RFID investment integrated to a manual production control system-a case study. Int. J. Adv. Manuf. Technol., vol. 66, MAY, pp. 987–1002

139. Topham, D; Harrison, D. 2008. The conceptual design of products benefiting from integrated micro-features. ESTC 2008: 2ND ELECTRONICS SYSTEM-INTEGRATION TECHNOLOGY CONFERENCE, VOLS 1 AND 2, PROCEEDINGS, SEP 01–04, 2008, pp. 1311–1316

140. Tornatzky, L; Fleischer, M. 1990. The process of technology innovation, Lexington, MA: Lexington Books

141. Tsai, CK. 2010. The construction of a collaborative-design platform to support waste electrical and electronic equipment recycling. Robotics and Computer-Integrated Manufacturing 26(1), February, pp. 100-108.

142. Ulewicz, S; Schutz, D; Vogel-Heuser, B. 2014. Integration of Distributed Hybrid Multi-Agent Systems into an Industrial IT Environment. 2014 12TH IEEE INTERNATIONAL CONFERENCE ON INDUSTRIAL INFORMATICS (INDIN), JUL 27–30, 2014, pp. 519–525

143. Uriondo, A; Esperon-Miguez, M; Perinpanayagam, S. 2014. The present and future of additive manufacturing in the aerospace sector: A review of important aspects. Proc. Inst. Mech. Eng. Part G-J. Aerosp. Eng., vol. 229, SEP, pp. 2132–2147
144. Vaia, RA. 2012. Nanomaterials and Future Aerospace Technologies: Opportunities and Challenges. MICRO- AND NANOTECHNOLOGY SENSORS, SYSTEMS, AND APPLICATIONS IV, APR 23–27, 2012
145. Venkatasubramanian, V. 2005. Prognostic and diagnostic monitoring of complex systems for product lifecycle management: Challenges and opportunities. Comput. Chem. Eng., vol. 29, MAY 15, pp. 1253–1263
146. Vezzoli, C; Ceschin, F; Diehl, JC; Kohtala, C. 2015. New design challenges to widely implement 'Sustainable Product-Service Systems'. J. Clean Prod., vol. 97, JUN 15, pp. 1–12
147. Wahab, A; Khalid, A; Nawaz, R. 2014. Non-Contact Metrology Inspection System for Precision Micro Products. 2014 INTERNATIONAL CONFERENCE ON ROBOTICS AND EMERGING ALLIED TECHNOLOGIES IN ENGINEERING (ICREATE), APR 22–24, 2014, pp. 151–156
148. Walters, AT; Millward, H. 2011. Challenges in managing the convergence of information and product design technology in a small company. Int. J. Technol. Manage., vol. 53, Apr 2, pp. 190–215
149. Wang, ED; Yuan, C. 2014. A hybrid life cycle assessment of atomic layer deposition process. J. Clean Prod., vol. 74, JUL 1, pp. 145–154
150. Wang, Y; Chen, Y; Benitez-Amado, J. 2015. How information technology influences environmental performance: Empirical evidence from China. Int. J. Inf. Manage., vol. 35, APR, pp. 160–170
151. Winter, J; Ronkko, K; Rissanen, M. 2014. Identifying organizational barriers – A case study of usability work when developing software in the automation industry. J. Syst. Softw., vol. 88, FEB, pp. 54–73
152. Wu, W; Hirogaki, T; Aoyama, E. 2012. Investigation of Synchronous Accuracy of Dual Arm Motion of Industrial Robot. PROCEEDINGS OF PRECISION ENGINEERING AND NANOTECHNOLOGY (ASPEN2011), NOV 16–18, 2011, pp. 234–239
153. Xu, J; Huang, E; Chen, CH; Lee, LH. 2015. Simulation Optimization: A Review and Exploration in the New Era of Cloud Computing and Big Data. Asia Pac. J. Oper. Res., vol. 32, JUN
154. Yang, SH; Bagheri, B; Kao, HA; Lee, J. 2015. A Unified Framework and Platform for Designing of Cloud-Based Machine Health Monitoring and Manufacturing Systems. J. Manuf. Sci. Eng.-Trans. ASME, vol. 137, AUG
155. Yen, HR; Sheu, C. 2004. Aligning ERP implementation with competitive priorities of manufacturing firms: An exploratory study. Int. J. Prod. Econ., vol. 92, DEC 18, pp. 207–220

156. Yoo, DJ. 2014. Recent Trends and Challenges in Computer-Aided Design of Additive Manufacturing-based Biomimetic Scaffolds and Bioartificial Organs. Int. J. Precis. Eng. Manuf., vol. 15, OCT, pp. 2205–2217

157. Zhang, P; Wang, B; Liang, YC. 2010. Fabrication of microstructure array by means of ultra-precision micro-milling. 5TH INTERNATIONAL SYMPOSIUM ON ADVANCED OPTICAL MANUFACTURING AND TESTING TECHNOLOGIES: ADVANCED OPTICAL MANUFACTURING TECHNOLOGIES, APR 26–29, 2010

158. Zhang, XY; Zhang, YD. 2015. Tissue Engineering Applications of Three-Dimensional Bioprinting. Cell Biochem. Biophys., vol. 72, JUL, pp. 777–782

159. Zhang, YF; Wang, WB; Liu, SC; Xie, GN. 2014. Real-Time Shop-Floor Production Performance Analysis Method for the Internet of Manufacturing Things. Adv. Mech. Eng.

160. Zhao, QQ; Boxman, A; Chowdhry, U. 2003. Nanotechnology in the chemical industry – opportunities and challenges. J. Nanopart. Res., vol. 5, DEC, pp. 567–572

Annex II. Interview questionnaire

Project EASME/COSME/2014/014

An analysis of drivers, barriers and readiness factors of EU companies for adopting advanced manufacturing products and technologies

Interview questionnaire:

Drivers and Barriers of EU Companies for adopting Advanced Manufacturing Technologies

made by VTT, IDEA Consult, Fraunhofer ISI, ITIA

1 Questionnaire for AM users and suppliers

1.1 Background

The EU has found that European industry is a leader in production of Advanced Manufacturing Technologies (AMT), but is lagging behind other regions in its use of these technologies. This interview is part of the project ”an analysis of drivers, barriers and readiness factors of European companies for adopting advanced manufacturing products and technologies” funded by the European Commission. The objective of the project is to ascertain which factors are driving and which are slowing down diffusion of AM technology in the European industry and to make policy recommendation for EU based on the findings. The project is led by Fraunhofer ISI in Germany in cooperation with IDEA Consult from Belgium, ITIA from Italy and VTT from Finland.

The results of interviews in 15 companies will be used within the project to acquire an in-depth understanding of the drivers and barriers for use of AMT in European industry and to plan an industry survey. The interview answers of a single company will not be reported or published without the agreement of the company.

In this project, we are focusing on three main groups of advanced manufacturing technology: *high performance manufacturing technology, ICT-enabled intelligent manufacturing technology and sustainable manufacturing technology*. In the interview, we hope you will consider what all these three groups mean to your company.

The structure of the interview is based on four parts:

1. Part 1 on next page includes a list of potential AMT.
   Please use 3–5 minutes to get acquainted with them.
2. Part 2 of the interview focuses on the business of your company on a general level
3. Part 3 focuses on how your company utilize AM technology
4. Part 4 focuses on input for policy making

2 Advanced manufacturing technology

In Table 1 below we list a number of Advanced Manufacturing Technologies. These are at the focus of our study, but the list is not exclusive. You may have some other technologies in mind.

Table 1. Relevance of AMT

1.	High Performance Manufacturing Technologies
-	Industrial robots/ handling systems
-	Automated Warehouse Management Systems
-	Technologies for safe human-machine cooperation
-	Processing alloy construction materials
-	Processing composite materials
-	Manufacturing micromechanical components
-	Additive manufacturing
-	Other
4.	ICT-Enabled Technologies
-	VR / simulation in production reconfiguration
-	VR / simulation in product design
-	Supply chain management with suppliers/customers
-	Product Lifecycle Management Systems
-	Enterprise Resource Planning
-	Other
5.	Sustainable Manufacturing Technologies
-	Dry processing/minimum lubrication
-	Recuperation of kinetic and process energy
-	Control system for shut down of machines
-	Combined cold, heat and power (Bi-/Trigeneration)
-	Recycling and waste/disposal management technologies
-	Energy efficient technologies
-	Sustainable nanotechnology
-	Biomanufacturing
-	Other

3 Business environment

1. Describe your main business, products and services

2. How have market conditions for your products/services changed over the last five years?

3. What are your company's main competitive means?
   a. economics of scale (low cost due to high volume)
      a. low cost of labour
      b. high level of automisation
   b. high quality niche products
   c. flexibility and customization
   d. something else

4. How has the competitive situation developed over last five years?

5. What has your company's (business unit's) financial situation been like over the last five years? What are the main factors affecting the financial situation?

6. On a scale from 1 – 5 (1 = basic level, 3 = average industry level, 5 = leading edge technology), how would you describe the technological level in your company? Why?
   a. product technology
   b. production technology
   c. use of ICT technology
   d. Management support to improve technological level

4 Use of AMT

1. What could be the drivers and barriers for European companies to invest in AMT?
   a. In High Performance Manufacturing Technologies
   b. In ICT-Enabled Technologies
   c. In Sustainable Manufacturing Technologies

2. How is national and European policy supporting or preventing investment in AMT in your country or Europe?

3. What AM technologies have you invested in, and why?
   What were the main drivers for investing?

4. What AM technologies have you decided not to invest in, and why?
   What were the main barriers to investment?

5. Regarding the investment you have already made (see above), how did the following drivers and barriers affect your investment decision?

6. Regarding the technology you are interested in but have not yet invested in: How have the following drivers and barriers affected your investment decision?

Positive Decision	How did it affect your investment decision? (5 high – 1 low)	Comments
Financial situation		
Demand Situation		
Competitive Situation		
Know-how, competence and skills		
Process performance		
Customer requirements		
Legislative, regulation, political situation		
Sustainability		
Other external drivers?		

7. Regarding the technology you are interested in but have not yet invested in: How have the following drivers and barriers affect the investment decision?

Negative Decision	How did it affect your investment decision? (5 high – 1 low)	Comments
Financial situation		
Demand Situation		
Competitive Situation		
Know-how, competence and skills		
Process performance		
Customer requirements		
Legislative, regulation, political situation		
Sustainability		
Other external drivers?		

8. You are also a provider of AMT. Based on your contacts with your clients can you indicate the dominant drivers and barriers that affect their investment decisions in Europe?

Decision Making	How did it affect your investment decision? (5 high – 1 low)	Comments
Financial situation		
Demand Situation		
Competitive Situation		
Know-how, competence and skills		
Process performance		
Customer requirements		
Legislative, regulation, political situation		
Sustainability		
Other external drivers?		

5 Input to policy making

1. How does regulation affect your business?

   a. Standards, certification and other qualification procedures
   b. Environmental regulation
   c. Tax framework
   d. Certification framework
   e. Regulatory conditions
   f. Other

2. In which of the above-mentioned areas do you think EU or national policy could motivate you to make additional investment, if yes, how?

3. What could EU do to improve the use of AMT in Europe?